

1985

Instrumentation and control of an engine generator set for biogas

Timothy M.P Wall
Iowa State University

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**INSTRUMENTATION AND CONTROL OF AN ENGINE GENERATOR SET FOR
BIOGAS**

Iowa State University

Ph.D. 1985

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Instrumentation and control of an engine
generator set for biogas

by

Timothy M. P. Wall

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major: Agricultural Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major/Department

Signature was redacted for privacy.

For the Graduate College

Members of the Committee:

Signature was redacted for privacy.

Iowa State University
Ames, Iowa

1985

TABLE OF CONTENTS

| | |
|--|-----------|
| GENERAL INTRODUCTION | Page 1 |
| Explanation of Dissertation Format | 2 |
| SECTION I. DATA LOGGING AND INSTRUMENTATION OF AN ENGINE GENERATOR SET | 3 |
| INTRODUCTION | 4 |
| Objectives | 6 |
| EQUIPMENT | 8 |
| Engine Generator | 8 |
| DATA LOGGER HARDWARE | 9 |
| Microcomputer and Interface | 9 |
| Analog Signals | 12 |
| Digital Signals | 24 |
| DATA LOGGER SOFTWARE | 39 |
| Calibration | 42 |
| RESULTS AND DISCUSSION | 56 |
| CONCLUSIONS | 75 |
| REFERENCES | 76 |
| APPENDIX ASSEMBLED LISTING OF THE ASSEMBLY LANGUAGE ROUTINE | 79 |
| SECTION II. CONTROL OF ENGINE IGNITION TIMING, AIR FUEL RATIO AND COOLANT TEMPERATURE FOR RESEARCH OF AN ENGINE GENERATOR SET | 86 |
| INTRODUCTION | 87 |
| Objectives | 93 |

| | |
|---|------------|
| EQUIPMENT | Page 94 |
| Timing Control | 95 |
| Air Fuel Ratio | 104 |
| Coolant Temperature | 105 |
| EXPERIMENTAL PROCEDURE | 106 |
| RESULTS AND DISCUSSION | 108 |
| CONCLUSIONS | 124 |
| REFERENCES | 125 |
| SECTION III. AIR FUEL RATIO CONTROL OF AN ENGINE GENERATOR SET | 128 |
| INTRODUCTION | 129 |
| Objectives | 133 |
| EQUIPMENT | 134 |
| Engine and Sensors | 134 |
| ELECTRONIC CONTROLLER DESIGN | 136 |
| RESULTS AND DISCUSSION | 144 |
| CONCLUSIONS | 146 |
| REFERENCES | 147 |
| SUMMARY AND DISCUSSION | 149 |
| APPENDIX LISTING OF THE BASIC PROGRAM USED BY THE DATA LOGGER | 152 |

GENERAL INTRODUCTION

Cogeneration of electricity and thermal energy with an engine generator set operating on biogas is an important part of an energy integrated farm system. To determine the overall viability of an energy integrated farm system, the amount of useful energy that can be recovered from biogas is an important factor.

Both laboratory and farm scale experimentation have been carried out on engine generators operating on biogas. Much of this work has been geared toward maximizing the production of electricity; little information however, has been gathered on the thermal energy recovery from an engine generator.

In the automotive industry, electronic control of engines is a topic that has become well-refined in the 1980s. It is feasible that some of these controls could be applied to an engine generator set to improve its overall efficiency.

The objectives of the work here are to:

1. Develop an instrumentation and data logging system that can be used to evaluate the performance of an engine generator set for various operating conditions.

2. Develop a method to control engine ignition timing, air fuel ratio and coolant temperature for research purposes. Find the optimum combination of these three variables for the cogeneration of electrical and thermal energy.

3. Construct a simple control system for an engine generator set to maintain optimum engine ignition timing, air fuel ratio and coolant temperature.

Explanation of Dissertation Format

This dissertation is presented in the alternate format as specified by the Thesis Office at Iowa State University. It contains three papers, each addressing one of the objectives stated in the General Introduction. For completeness, the dissertation contains an Appendix that shows a listing of the BASIC software program used by the data logger. This Appendix is not referenced in any of the papers.

SECTION I. DATA LOGGING AND INSTRUMENTATION
OF AN ENGINE GENERATOR SET

Timothy M. P. Wall, M.S.

R. J. Smith, Ph.D.

S. J. Marley, Ph.D.

From the Department of Agricultural Engineering,
Iowa State University, Ames, IA 50011

INTRODUCTION

Integrated farm energy systems use engine generators to convert biogas into electric power and thermal energy (Stahl et al. 1982; Siebenmorgen et al. 1983). In each system the overall performance of the engine generator has been evaluated under operating conditions. These studies were carried out under farm conditions with limited engine instrumentation. By operating an engine generator under laboratory conditions with instrumentation capable of updating the engine's performance at the rate of at least once a minute, a system of controls can be developed that will operate an engine generator in farm environments.

Stahl et al., in their engine generator evaluation, computed results every 10 minutes (Stahl et al. 1982). With the advance of computers and electronics it is possible to obtain results at a rate better than once a second. In agriculture, data logging on tractors using commercial data loggers has been demonstrated, but with a maximum data recording rate of once a minute (Culpepper 1979). Instrumentation for engines has been accomplished primarily in the automotive industry. A system called DIGTAP is a data acquisition and processing system used to produce

pressure volume diagrams of engines (Douaud and Eyzat 1977). For this project, there is greater interest in the manner in which an existing engine performs; the instrumentation and data logging system needs to be designed to measure variables related to fuel consumption and power produced.

Other data loggers used in the automotive field are for collecting vehicle operation data to be loaded into main frame computers for analysis (White 1983). A review of minicomputer and microcomputer systems shows that microcomputers incorporated in commercial data loggers with built-in signal conditioning and electrical noise immunity have many uses (Johnson and Wipperfuth 1981). Most systems included some custom built interface boards connected to a microcomputer with the computer doing gain and offset calculations to convert readings from sensors to meaningful numbers (Flis and Wallace 1978). The general trend for data logging is to have a stand alone microcomputer connected to an interface, which should, if possible, be commercially built and have signal conditioning.

The sensors or transducers used on the engine are vital parts of an instrumentation system. A survey of engine sensors shows an emphasis on producing accurate low cost sensors (Fleming 1982). These engine sensors are for knock, crankshaft position, mass air flow, and torque measurement.

Engines operating on natural gas (methane) do not show signs of severe engine knock, if any knock at all (Karim and Ali 1975). With the engine of an engine generator set running at constant speed the performance can be measured from the power produced by the generator without measuring engine torque. For this project, where the prime interest is performance of the engine when producing electricity and thermal heat, the primary engine sensors are a mass air flow sensor and a crankshaft position sensor for speed measurement and control of engine timing. Other sensors available included manifold absolute pressure, manifold vacuum, ambient absolute pressure, oxygen partial pressure, fuel flow, coolant temperature, exhaust gas flow and ambient humidity (Wolber 1980). Many of these sensors are incorporated in modern automobile control systems (Derato 1982). This indicates that developing an engine generator control system for on-farm use may not be very expensive to implement with existing automotive engine sensors.

Objectives

1. Develop an instrumentation and data logging system to measure engine parameters for evaluating an engine generator set.
2. Use commercially available engine sensors.

3. Operate with a data collection period fast enough to allow adequate insight into the operation of the engine.
4. Produce reliable and repeatable results.
5. Ability to calculate engine parameters from collected data.

EQUIPMENT

Engine Generator

In general, a criterion for this project is to use equipment that is readily available for purchase and use on a farm. For this reason, a Kohler 7500 Watt standby generator set (Kohler Co.,¹ Kohler, WI 53044) is used for the tests. The engine generator is designed for use with gasoline, natural gas, or propane; but it was supplied with a natural gas carburetor. Operating on natural gas the system is rated at 6000 Watts. The generator is synchronous and connected to a variable resistive load. The engine generator is installed in the laboratory and connected to a natural gas supply. Natural gas is used for all the experimental work, and currently no attempt has been made to introduce carbon dioxide to the gas supply to simulate biogas. For all the experiments natural gas is assumed to be 100% methane. The contents of natural gas does vary and this may cause some errors in the results.

¹Mention of commercial products does not imply endorsement of these products by Iowa State University.

DATA LOGGER HARDWARE

Microcomputer and Interface

Figure 1 shows the data logging system and includes the engine parameters to be measured. The data logger is not only designed to collect data but also to calculate the engine parameters, print and store the results on floppy disc. To do this, a microcomputer was selected as the center of the system. For this project an Apple II computer (Apple Computer Inc., 10260 Bandley Drive, Cupertino, CA 95014) with one floppy disk drive and an Epson MX-80 dot matrix printer (Epson America, Inc., 3415 Kashiwa Str., Torrance CA 90505) are used.

Apple II

An Apple II computer is a 6502 based machine that can be programmed in BASIC. Assembly language routines can easily be accessed from the main BASIC program. Slots are provided in the chassis of the computer for hardware interface cards to be inserted. Parallel and serial interface cards are used to interface the Apple II with the data collection system.

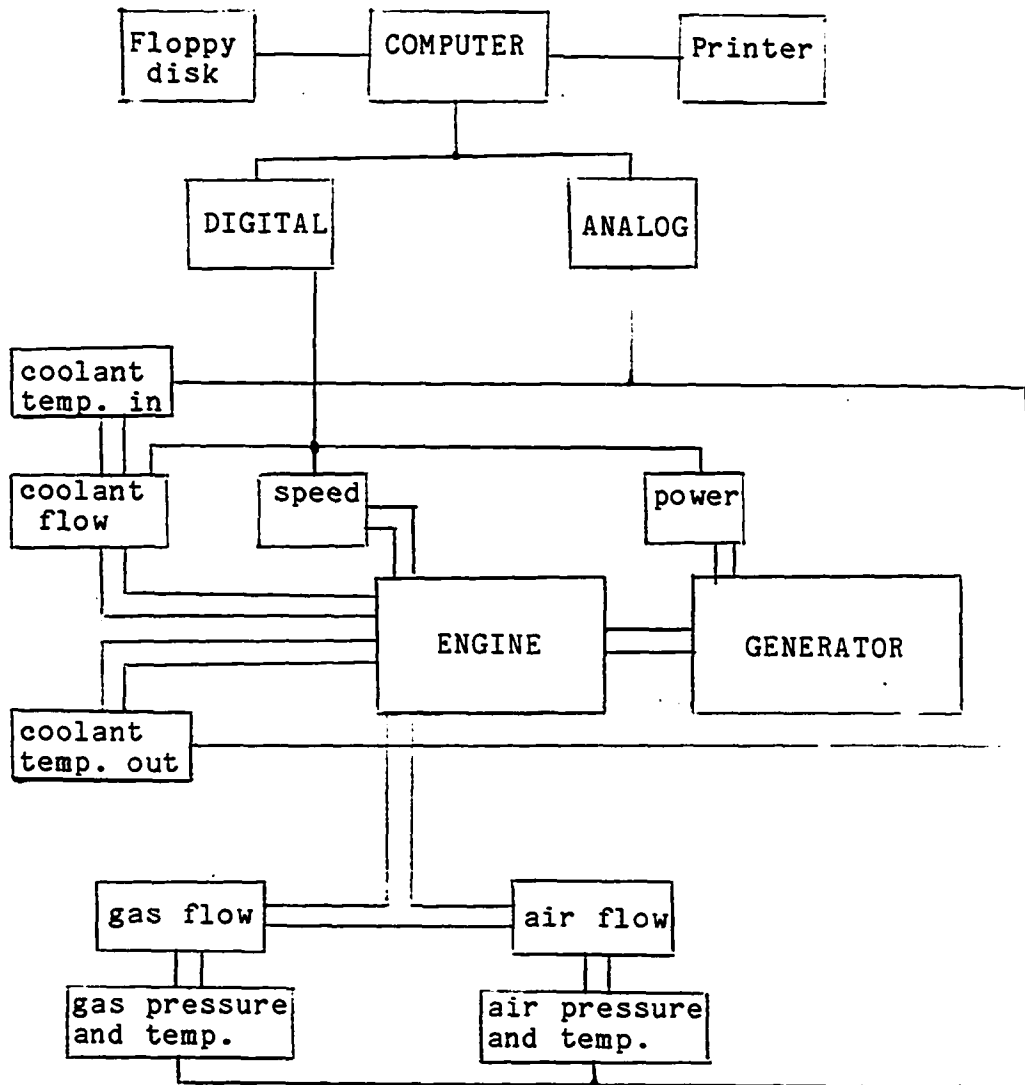


Figure 1. Data logger and instrumentation system

Data collection

Analog and digital signals are the two types of signals that need to be interpreted by the data logger. An analog signal is an electric signal which can vary in amplitude to any value within the range that a particular device can produce (e.g., 0-5 V) and a digital signal is one which changes abruptly between two levels (e.g., high or low). The type of digital signals used are transistor transistor logic (TTL) with a high value of greater than 3 V. and a low of less than 0.2 V.

Below is a list of the engine parameters measured on the engine and an indication of the type of signal from each sensor.

Analog:

- air temperature
- gas temperature
- coolant inlet temperature
- coolant exit temperature
- pressure drop across the gas meter
- pressure drop across the air flow meter
- gas pressure
- oxygen sensor in the exhaust gas
- exhaust temperature.

Digital:

coolant flow rate
electrical power output
engine rpm.

The analog signals are all interfaced with the computer via the serial interface card and a MicroMac-4000 (Analog Devices Inc., Route 1 Industrial Park, P.O.Box 280, Norwood, MA 02062). The digital signals are interfaced via the parallel card and counter circuits built in the laboratory.

Analog Signals

MicroMac-4000

The MicroMac-4000 is a versatile measurement and control system (Analog Devices 1981). It is a microcomputer based system on a single board and provides a variety of signal conditioning options. In this experiment, the board is only used to read in analog signals, although the board is designed to input and output digital signals and can be expanded to output analog signals.

There are twelve analog input channels divided into blocks of four. Each block of four goes to a QMX module that conditions the input signal. The MicroMac-4000 measures, stores, and transmits the channel input in terms of dc voltage, dc current, degrees centigrade or fahrenheit,

or 0 to 100%. The type of QMX module and the setting of on the board DIP switches determine the type of analog signal read. A 12 bit analog to digital converter is used by the board and it scans each channel at a rate of twice a second. Only the most recent data are transferred to the host computer when requested. Table 1 gives a list of MicroMac-4000 channels used.

Table 1. MicroMac-4000 analog channels

| Channel | Purpose | Units |
|---------|------------------------------|-------|
| CH0 | Exhaust oxygen sensor | V |
| CH1 | Gas flow meter pressure drop | V |
| CH2 | Gauge gas pressure | V |
| CH3 | Air flow meter pressure drop | V |
| CH4 | Coolant exit temperature | C |
| CH5 | Coolant inlet temperature | C |
| CH6 | Gas temperature | C |
| CH7 | Air temperature | C |
| CH8 | Exhaust temperature | C |

Temperature sensors

The temperature sensors are AD590s (Intersil 1981), which are two terminal integrated circuits. Calibration is at 298.2 K (25 C) when the sensor has an output of 298.2 μ A that changes at a the rate of 1 μ A/K. The direct current produced is unaffected by changes in voltage supply (+4 to +30 V) to the sensor. These sensors have a range of -50 to +150 C, which is sufficient for the temperatures

measured in this project. An external 12 V supply is used to energize the sensors and a QMX02 module is used on the MicroMac-4000 board with 210 ohm shunt resistors (Analog Devices 1981). The DIP switches are set so that the temperature readings are in degrees centigrade. This type of temperature sensor is used to measure the coolant inlet and exit, gas, and air temperatures.

Exhaust temperature

The temperature of the exhaust gas is measured with a type K thermocouple attached to the exhaust pipe with a pipe clamp. The location is near the oxygen sensor so that the operating temperature of the sensor is known. The thermocouple is connected to a QMX03 module and the MicroMac-4000 DIP switches are set to transmit temperatures in degrees centigrade. The MicroMac-4000 is equipped with cold junction compensation.

Gas flow rate

Instantaneous volumetric flow rates of gases can be obtained by either using an obstruction meter or a laminar flow element (Doebelin 1983). Obstruction meters have the disadvantage of the flow rate being proportional to the square root of the pressure drop across the orifice. This

leads to a variation in the flow rate error over the range of the meter, although large flow rates can be measured with a small pressure drop. In laminar flow meters, the flow rate is proportional to the pressure drop across the laminar element.

$$Q = \frac{\pi D^4}{128 \mu L} \Delta p$$

where

Q = volume flow rate, m^3/s

D = tube inside diameter, m

μ = gas viscosity, Pa.s

L = element length, m

Δp = pressure drop across element, Pa.

To determine the element's dimensions an estimate of the gas flow rate into the engine is made. Assuming the engine and generator combined have an efficiency of about 18% at an output of 6 kW then:

$$\text{gas energy required} = 6000 / 0.18 = 33\,333 \text{ W.}$$

Assuming natural gas to be 100% methane, the lower heat of combustion is $50.1 \times 10^6 \text{ J/kg}$ (Perry and Green 1984) giving

$$\text{mass flow rate} = 33\,333 / 50.1 \times 10^6 \times 3600 = 2.4 \text{ kg/h.}$$

Natural gas is supplied at a pressure of about 103100 Pa.abs. and a temperature of about 25 C. By using the ideal

gas equation $pV = mRT$ (Levine 1978) the density of the supplied natural gas is 0.6652 kg/m^3 . Therefore

$$Q_T = 2.4 / 0.6652 = 3.61$$

where

$$Q_T = \text{volumetric flow rate } \text{m}^3/\text{h}.$$

In buildings natural gas is supplied at a gauge pressure of 1750 Pa. To maintain a positive gas pressure to the engine, the pressure drop across the gas flow element can be no greater than 1750 Pa. For this design a pressure drop of 1250 Pa. was chosen.

Laminar flow elements are expensive to buy. They consist of a number of small tubes each having laminar gas flow through it. For this project a laminar flow element was constructed by sealing small copper tubes (1.651 mm inside diameter) in a large gas pipe (25.4 mm inside diameter). For laminar pipe flow the Reynolds number must be less than 2000.

$$Re = \rho V D / \mu$$

where

$$Re = \text{Reynolds number} < 2000$$

$$\rho = \text{gas density} = 0.6652 \text{ kg/m}^3$$

$$D = \text{tube diameter} = 1.651 \times 10^{-3} \text{ m}$$

$$\mu = \text{gas viscosity} = 1.1 \times 10^{-5} \text{ Pa.s}$$

$$V = \text{gas velocity, m/s.}$$

Rearranging and substituting in the values

$$V < 20.0 \text{ m/s.}$$

Converting this to a volumetric flow rate in the tubes

$$Q < 4.29 \times 10^{-5} \text{ m}^3/\text{s.}$$

Minimum number of tubes

$$N_{\min} = Q_T / Q$$

$$N_{\min} = (3.61 / 3600) / 4.29 \times 10^{-5}$$

$$N_{\min} = 24$$

where

N = number of small tubes.

The flow will always be laminar if 24 or more tubes are used and the pressure drop does not exceed 1250 Pa.

Substituting the above numbers into the element flow equation the relationship between element length and the number of tubes needed for this application is derived.

$$Q_T / N = \frac{\pi D^4}{128 \mu L} \Delta p$$

$$N = 48.4 \times L$$

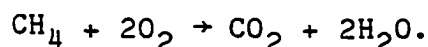
Because of the position of the engine a convenient value for L is 0.75 m, setting the number of tubes (N) to 36. The 36 copper tubes are placed inside the gas supply pipe and sealed with caulk. Calibration of the flow meter was made with element installed (see Data Logger Software).

The pressure drop across the laminar element is

measured with a differential pressure transducer with a range of 0 to 1245 Pa. and a voltage output of 0 to 5 V (Setra, 45 Nagog Park, Acton, MA 01720). This signal is connected directly to the MicroMac-4000 module QMX01 with the DIP switches set to transmit data values of 0 to 5 V to the Apple II.

Air flow rate

The flow rate of air into the engine is also measured with a laminar flow element. By calculating the stoichiometric air flow rate required at full engine load, the size of laminar element can be determined. The engine is operating on methane giving the following combustion equation:



Since each g-mol of methane requires two g-mols of oxygen, and dry air contains 21% oxygen, 9.524 g-mols of dry air are required. Methane and air have molecular weights of 16 and 29, respectively. The stoichiometric mass air fuel ratio is

$$A/R_{\text{st}} = 9.524 \times 29 / 16 = 17.26.$$

Density of dry air at one atmosphere and 25 C is 1.20 kg/m³ (Perry and Green 1984).

$$\begin{aligned}\text{Volumetric flow rate of air} &= 17.26 \times 2.4 / 1.20 \\ &= 34.52 \text{ m}^3/\text{h}.\end{aligned}$$

A commercial laminar flow element with a maximum flow capacity of $37.4 \text{ m}^3/\text{h}$ and a pressure drop of 3000 Pa. was available to use (Meriam Instruments, 10920 Madison Ave., Cleveland, OH 44102). The calibration curves were supplied with the meter.

Having selected one pressure transducer with a 0 to 5 V output, it is beneficial to have the other pressure transducers either produce, or be conditioned to produce, the same signal to make maximum use of the full 12 bit analog to digital conversion. For the air flow meter the pressure drop at maximum flow rate is about 2773 Pa. A PX164-010D differential pressure transducer (Omega, One Omega Drive, Box 4047, Stamford, CT 06907-0047), has a range of 0 to 2490 Pa. but gives a signal 1 to 6 V when energized by a required 8.0 V supply. This signal is conditioned before being connected to the MicroMac-4000. The gas pressure is also measured with a differential pressure transducer being used as a gauge pressure transducer by leaving the second port open to the atmosphere. The gauge pressure of the gas is about 1750 Pa. This pressure is measured with a PX162-027D (Omega) differential pressure transducer which has a differential

range of 0 to 6895 Pa. and signal output of 1 to 6 V when energized by an 8.0 V supply. This transducer signal is also conditioned before being connected to the MicroMac-4000.

Signal conditioning is accomplished by using two operational amplifiers in the standard inverting configuration (National Semiconductor 1977). The gain and offset for the signal is adjusted independently (see Figure 2).

$$V_p = 15 R_1/R_5 + V_o R_3 \times R_1/R_4 \times R_2$$

where

V_p = voltage from the pressure transducer, V

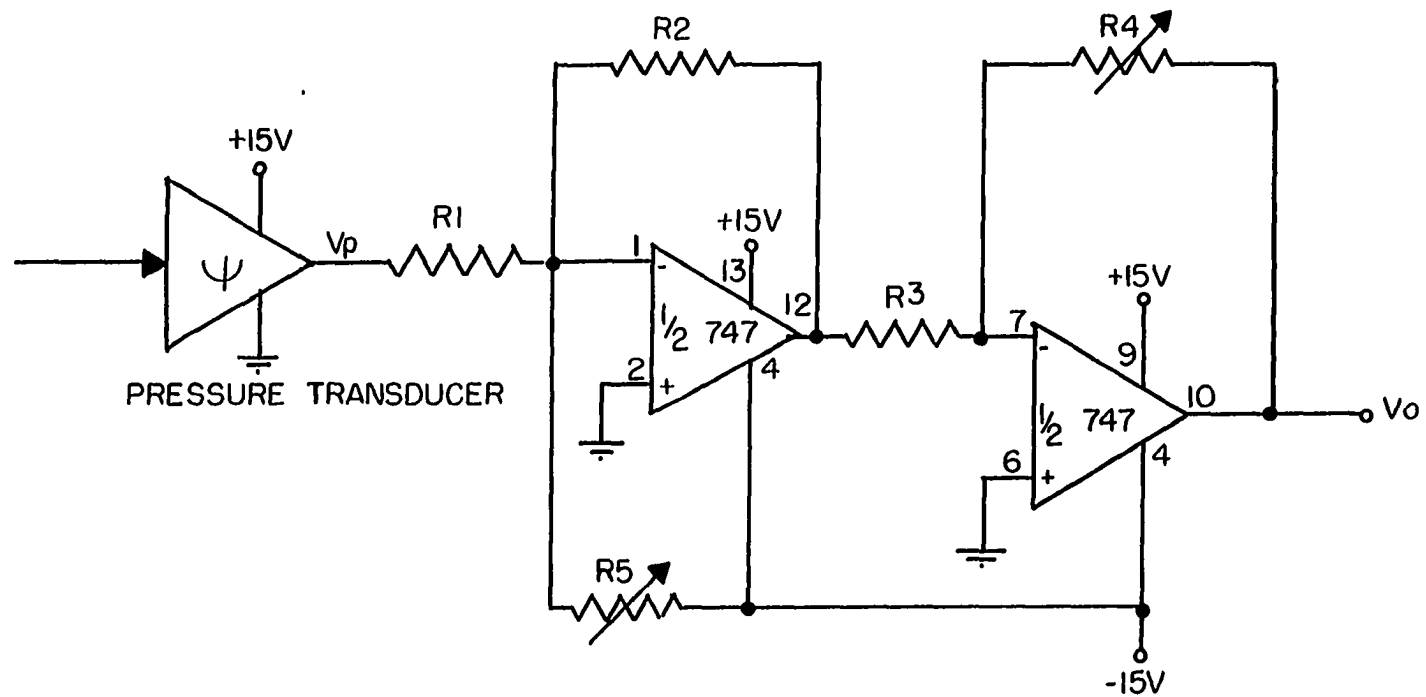
V_o = conditioned signal (0 to 5 V)

R_1 to R_5 = resistors shown in Figure 2, Ω .

For the air flow meter transducer $R_1 = R_2 = R_4 = 10 \text{ k}\Omega$ and $V_p = 1$, when $V_o = 0$ and $V_p = 6$, when $V_o = 5 \text{ V}$. Substituting into the equation gives the range for the variable resistors of $R_4 = 10 \text{ k}\Omega$ and $R_5 = 150 \text{ k}\Omega$.

For the gas pressure transducer $R_1 = 20 \text{ k}\Omega$, $R_2 = 70 \text{ k}\Omega$, $R_3 = 10 \text{ k}\Omega$ and $V_p = 1$, when $V_o = 0$ and $V_p = 2.27$ when $V_o = 5 \text{ V}$. Substituting into the equation gives the range for the variable resistors of $R_4 = 11.3 \text{ k}\Omega$ and $R_5 = 300 \text{ k}\Omega$.

The outputs from the operational amplifiers are connected directly to the MicroMac-4000 using the same



SCHEMATIC I

Figure 2. Pressure transducer signal conditioning

module as the gas flow transducer that is configured to transmit 0 to 5 V signals to the Apple II.

Oxygen sensor

The fourth channel on QMX01 module is used by the oxygen sensor in the exhaust. The exhaust gas oxygen sensor used is part of Ford Motor Company's electronic engine control system (Derato 1982). It is made of zirconium dioxide and generates its own voltage based on the oxygen content of the exhaust gas. With a low oxygen content (a rich fuel mixture) the voltage generated is from 0.6 to 1.0 V. The lean mixture voltage is less than 0.2 V. This sensor is connected directly to the QMX01 module without signal conditioning. No signal conditioning is used because it is possible that this sensor could be used as part of an automatic engine control system, and a reading of the actual voltage produced may be beneficial for further control design.

Serial interface

The MicroMac-4000 communicates with a host computer via an RS-232 serial interface (Seyer 1984). In this system only the data out (XMIT DATA), data in (RCV DATA) and ground (GND) lines (Analog Devices 1981) are connected to the Apple

II serial card with the request to send (RTS), data terminal ready (DTR) and the clear to send (CTS) lines of the MicroMac-4000 left open. Communication is in conventional asynchronous ASCII format consisting of 7 data bits, one parity and one or two stop bits. DIP switches on the MicroMac-4000 board are set for even parity, two stop bits and a 9600 baud rate.

The serial card in the Apple II is an AIO Apple interface (SSM Microcomputer Products, 2190 Paragon Drive, San Jose, CA 95131). This card uses a Motorola asynchronous communication interface adapter (ACIA) MC6850 (Haskell 1983). The card is placed in slot 7 of the Apple II, and the registers of the ACIA can be directly accessed with POKE and PEEK commands from the resident BASIC program (SSM Microcomputer products 1979). By using POKE -16140,3 and POKE -16140,1 the ACIA is cleared and set to 7 data bits, even parity, two stop bits and, with the correct on the card switch selection, a baud rate of 9600.

To allow the serial card to communicate with the MicroMac-4000 the RTS, CTS, DTR and data carrier detect (DCD) lines of the card are connected to +12 V. The transmitted data (TD), receive data (RD) and signal ground (SG) are respectively connected to RCV DATA, XMIT DATA and GND of the MicroMac-4000. The communication with the

MicroMac-4000 is discussed in the software section (see Data Logger Software).

Digital Signals

Parallel interface

A parallel interface card (John Bell Engineering, Inc., 400 Oxford Way, Belmont, CA 94002) is used to communicate with the digital hardware built in the laboratory. This interface comprises two versatile interface adapters (VIA) 6522 (Rockwell International 1978). The VIA consist primarily of two bi-directional ports and two 16-bit counters and is programmable. For this project the card is placed in slot 5 of the Apple II. The VIA registers are located at the Apple II memory locations listed in Table 2.

Initializing the VIAs

The VIA's bidirectional ports A and B (pins PA0-PA7 and PB0-PB7) can be individually programmed so that each pin can either act as an input or an output under the control of the Data Direction Registers (DDRA, DDRB) which are set during initialization. To make a pin an input, a "0" corresponding to that pin must be in the Data Direction Register; similarly a "1" corresponding to an output.

Table 2. Memory locations of VIA registers

| VIA registers | | Apple memory loc. | |
|---------------|----------------------------|-------------------|--------|
| code | description | decimal | hex. |
| ----- | | | |
| VIA #1 | | | |
| ORB/IRB | Output/input register B | -15104 | \$C500 |
| ORA/IRA | Output/input register A | -15103 | \$C501 |
| DDRB | Data direction register B | -15102 | \$C502 |
| DDRA | Data direction register A | -15101 | \$C503 |
| T1R-L | Timer one register lower | -15100 | \$C504 |
| T1R-H | Timer one register higher | -15099 | \$C505 |
| ACR | Auxiliary control register | -15093 | \$C50B |
| VIA #2 | | | |
| ORB/IRB | Output/input register B | -14976 | \$C580 |
| ORA/IRA | Output/input register A | -14975 | \$C581 |
| DDRB | Data direction register B | -14974 | \$C582 |
| DDRA | Data direction register A | -14973 | \$C583 |
| T1R-L | Timer one register lower | -14972 | \$C584 |
| T1R-H | Timer one register higher | -14971 | \$C585 |
| ACR | Auxiliary control register | -14965 | \$C58B |
| ----- | | | |

Only VIA #2 is used by the data logger to input data.

Figure 3 shows VIA #2 connected to the data lines of the counters and the multiplexing system used to read individual counters. Port A is used to input data and DDRA is set to 0 by the BASIC command POKE -14973,0. Pins PB0 - PB6 are signal output pins. Register DDRB is set to 127 by POKE -14974,127.

Pin PB7 is used for timing control of the flow meter counters. To determine the flow rate of liquid through flow meters that produce TTL pulses at a rate proportional to the flow, the pulses are counted for a fixed period of time. To achieve this, the output of each meter is connected to a 16

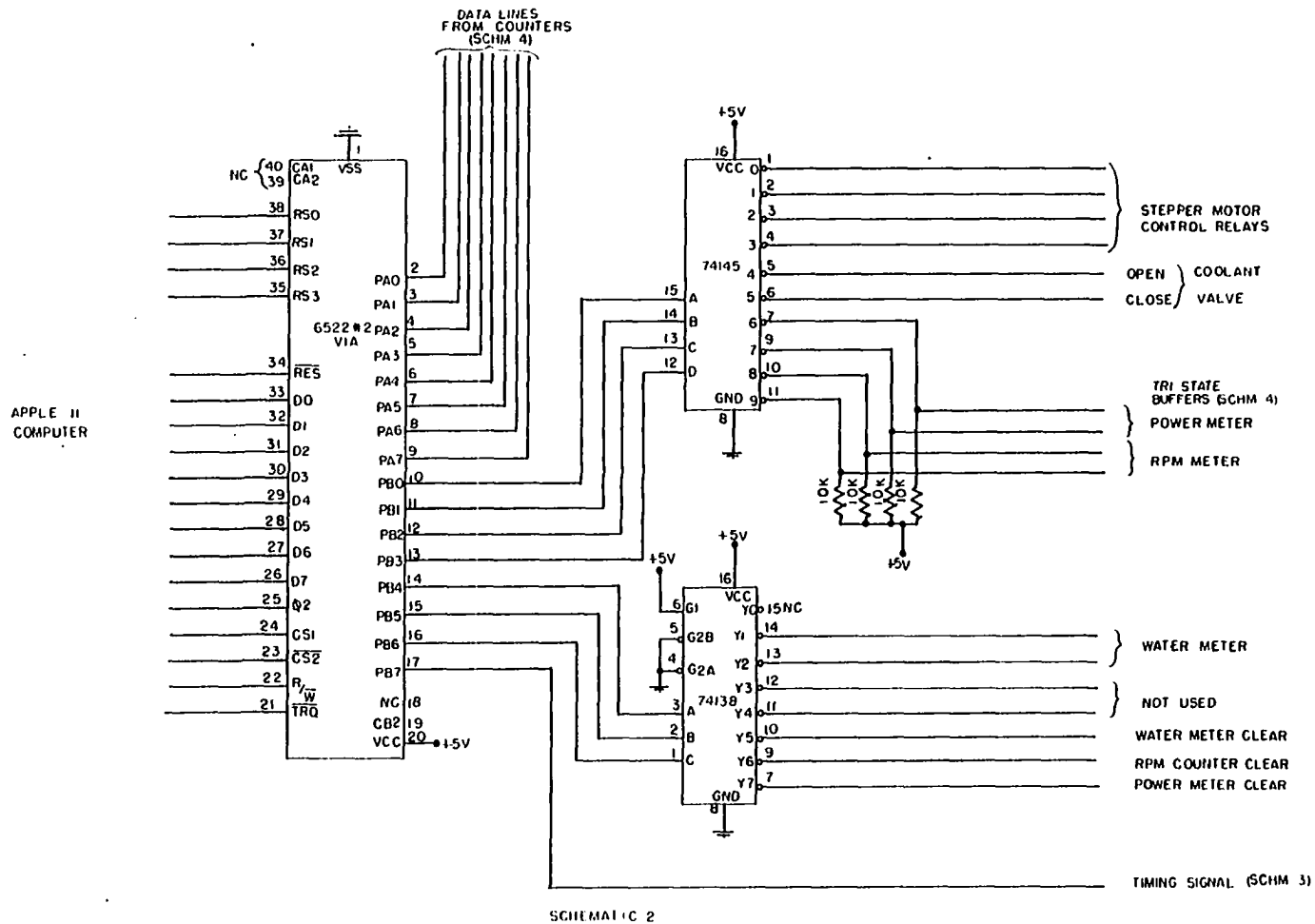


Figure 3. Multiplexing and control circuit

bit counter and the pulses are stopped and started by hardware controlled by the Apple II's internal clock. A ten second timing period was chosen, and this was accomplished by stepping down the Apple II's 1 MHz clock (Apple II clock is actually 1.023 MHz; an adjustment is made in the software to correct timing errors in flow rates) with the 16 bit counter in VIA #2 and two 4 bit counters. The 4 bit counters (SN74161) are connected as ripple look-ahead counters (Texas Instruments 1976) that will count up to 255 before resetting to zero. For a 10 s time period output, these counters require a $10/256 = 0.39062$ s input clock period. This comes from PB7 of VIA #2.

The VIA internal counters can be used in several different ways (Rockwell International 1978). For this application, VIA #2 is initialized so that timer one counts down from a set value to zero at a rate equal to the system's clock. At zero the output of pin PB7 is inverted (i.e., high to low, or low to high), and the counter is returned to its preset value to begin the sequence again. The preset value is determined by the rate at which pin PB7 is required to oscillate. The 4 bit counters need a 0.039062 s clock input; but since the SN74161s are positive edge triggered counters, pin PB7 has to invert twice every 0.039062 s to trigger the counters. For this to happen the

internal VIA counter must reach zero at $0.039062/2 = 0.019531$ s intervals. A preset value of 19531 declining at the system clock rate of 1 MHz accomplishes this.

Conditioning pin PB7 to toggle is done during the initialization of the VIAs. When the respective bits ACR6 and ACR7 of the Auxiliary Control Register (ACR) in the VIA are set to "1", pin PB7 will generate a continuous square wave. The decimal value required in the ACR is given by:

$$ACR = 2^6 + 2^7 = 192.$$

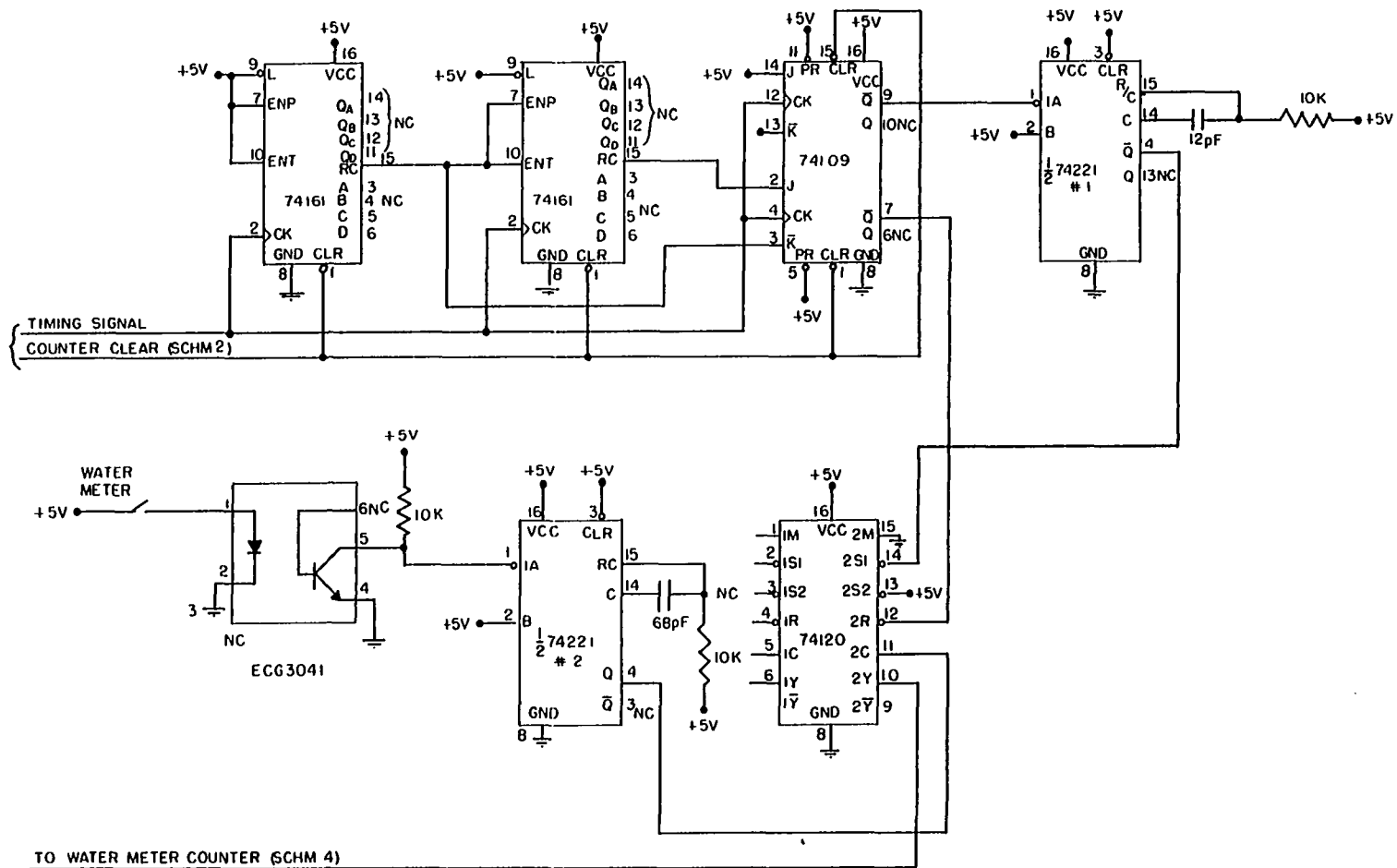
Using the BASIC command POKE -14965,192, VIA #2 will be initialized for PB7 to toggle. During initialization, the internal 16 bit counter has to be set to 19531. Since the Apple II is an 8 bit machine, only numbers of up to 255 can be transferred at one time and the 16 bit counter has to be loaded in two halves. The least significant 8 bits are first loaded into Timer one register lower (T1R-L); then the most significant 8 bits are loaded into Timer one register higher (T1R-H), such that the net effect is the number 19531 in the 16 bit counter. The two 8 bit numbers are determined by:

Most significant

| | | | | | | | | |
|------------------------------|----------------|----------|----------|----------|----------|----------|-------|-------|
| | 2^{15} | 2^{14} | 2^{13} | 2^{12} | 2^{11} | 2^{10} | 2^9 | 2^8 |
| | 32768 | 16384 | 8192 | 4096 | 2048 | 1024 | 516 | 256 |
| 19531 = | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| | + 75 remainder | | | | | | | |
| binary 0100110 = 76 decimal. | | | | | | | | |

The most significant 8 bits = 76 and the least significant = 75. The BASIC command POKE -14972,75 followed by POKE -14971,76, after ACR initialization, will enable pin PB7 of VIA #2 to continually toggle with a period of 0.039062 s.

Figure 4 shows the complete timing circuit including a dual positive edge triggered flip-flop, SN74109 and dual pulse synchronous drivers, SN74120 (Texas Instruments 1976). The SN74120 chips are used to start and stop the pulse train from the flow meters. A signal to the SN74120 allows pulses to pass through to the flow meter counters. Another signal inhibits the pulse train after a started meter pulse has been completed. This insures no glitching of the counters. The SN74109 has both flip-flops used to control the SN74120. Once cleared by the software, the first positive edged pulse from PB7 changes the output state of one flip-flop, which triggers the SN74120 and counting starts. After 255 positive edged pulses from PB7, the SN74161 ripple carry output enables the other flip-flop which changes state on the 256th pulse and stops the pulse train through the SN74120. No further changes of state will occur until the counters are read and then cleared by the software. The SN74221 #2, monostable multivibrator, in Figure 4 is used to provide a pulse to the SN74120 rather than a permanent



SCHEMATIC 3

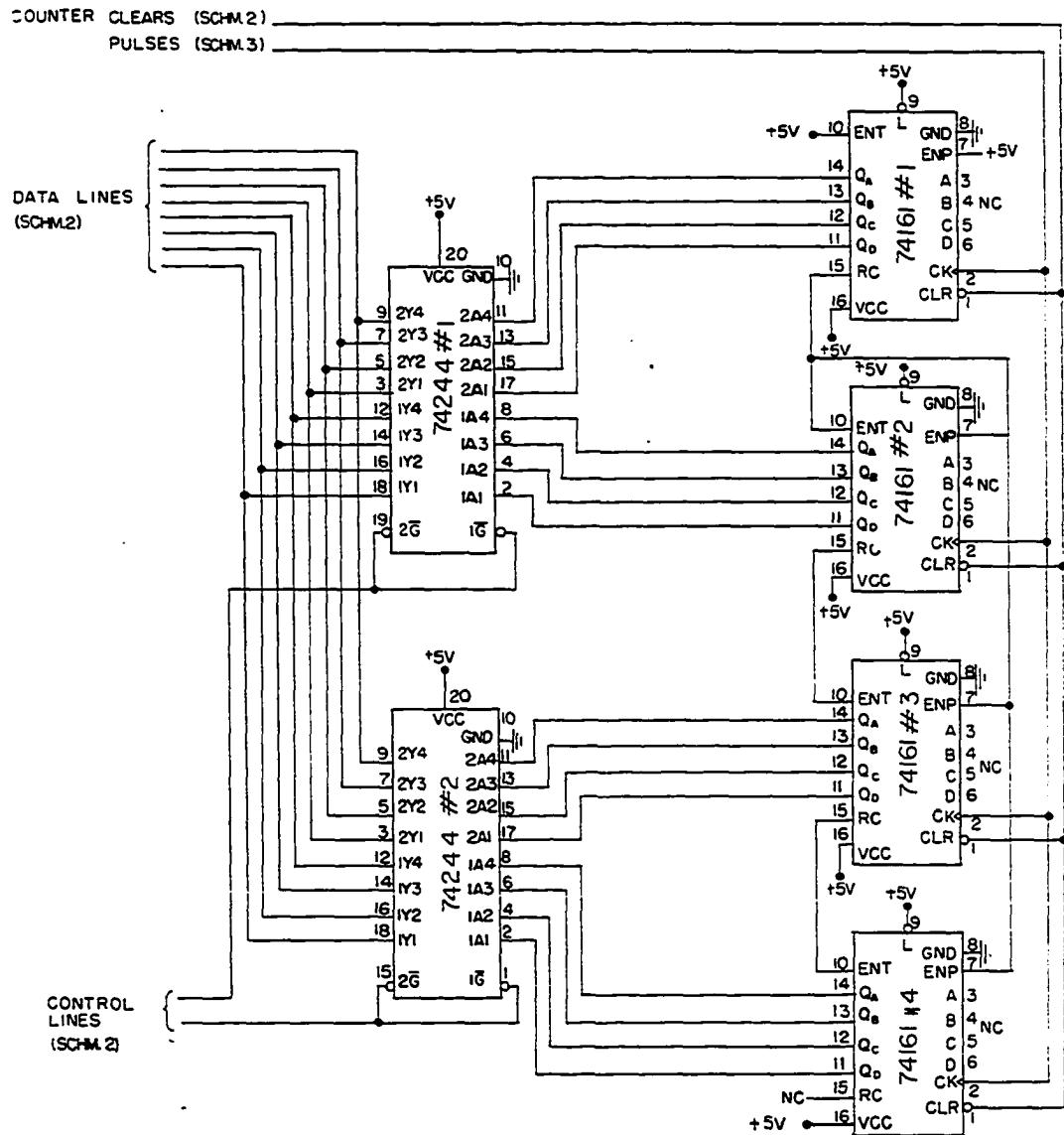
Figure 4. Timing circuit

change of state.

Counters

The coolant flow rate, engine RPM and electrical power measurements all use digital counters. The digital counters in this system are 16 bit counters comprising four 4 bit counters, SN74161, wired as ripple look-ahead counters (Texas Instruments 1976). Figure 5 shows one of the 16 bit counters and two SN74244, noninverting tristate buffers (Texas Instruments 1976), that are used to read the counters. Again the 16 bit counts have to be handled as two 8 bit counts by the Apple II. The 4 bit counters are taken in pairs with the output lines of each pair connected to one SN74244. When the \overline{G} inputs of the SN74244 are held high, the outputs of the counters are connected to port A of VIA #2. With low inputs at \overline{G} , the tristate buffer acts as an open circuit. By first reading one pair of counters that contains the least significant byte (LSB) and then the other set that contains the most significant byte (MSB), the actual 16 bit count (N) can be found by:

$$N = \text{LSB} + 256 \times \text{MSB}.$$



SCHEMATIC 4

Figure 5. Counters and tristate buffers

Coolant flow meter

To maintain a constant inlet temperature for the coolant the radiator of the engine is removed and tap water is used to cool the engine. The flow rate is measured by a CE700 Kent water meter (Kent Meter Sales, Inc., P. O. Box 1852, Ocala, FL 32678) which is a rotary flow meter that has a contact switch making 528 contacts per 10 liters. The flow rate is estimated to be 5 liters/min (Kohler 1981), which is 264 contacts/min or 44 pulses in 10 s. The contact switch needs to be connected to the interface and conditioned to produce TTL signals. This is accomplished by connecting the light emitting diode (LED) of an ECG3041 optoisolator (ECG 1985) to the meter terminals and a +5 V supply. Closing of the meter switch contacts illuminates the LED and turns on the internal phototransistor of the ECG3401. Figure 4 shows the ECG3041 and its connection to a SN74221 #2 dual monostable that produces about a 500 ns TTL pulse that goes to the SN74120.

Power and RPM measurement

Electric power is measured by a single-phase watthour meter type 1W-30-A (General Electric). This meter has a rating of $K_n = 3$ indicating that during one rotation of the meter disk, 3 Wh are recorded. To make this meter

compatible with the digital interface, a TTL signal from the meter is required. These meters have two small adjacent holes in the rotating disk that are used for meter calibration. By attaching an opto-coupled interrupter module, ECG3101, (ECG 1985) to the meter so that the LED emits through the disk holes, two signals per revolution can be obtained.

Figure 6 shows the wiring diagram complete with an optoisolator to protect the interface from accidental high voltage. The LM555 timer (National Semiconductor 1980) is used to produce a single TTL pulse each time the meter rotating disk holes pass the ECG3101 module. The length of time for this pulse must be greater than the time it takes for the hole to pass the ECG3101 at the minimum power measurement and less than the time it would take for the next hole to reach the ECG3101 again at the maximum power measurement. At a load of 900 W the disk rotation is $900/3 = 300$ rev/h. This is $3600/300 = 12$ s/rev and therefore a hole passes the opto interrupt every 6 s. At a load of 5500 W one rotation takes $3600 \times 3/5500 = 1.96$ s giving a signal about once a second. LM555 timers have a 50% duty cycle permitting resistor and capacitor values to be chosen (National Semiconductor 1980) that give a pulse width of about half a second (see Figure 6). This is sufficient for

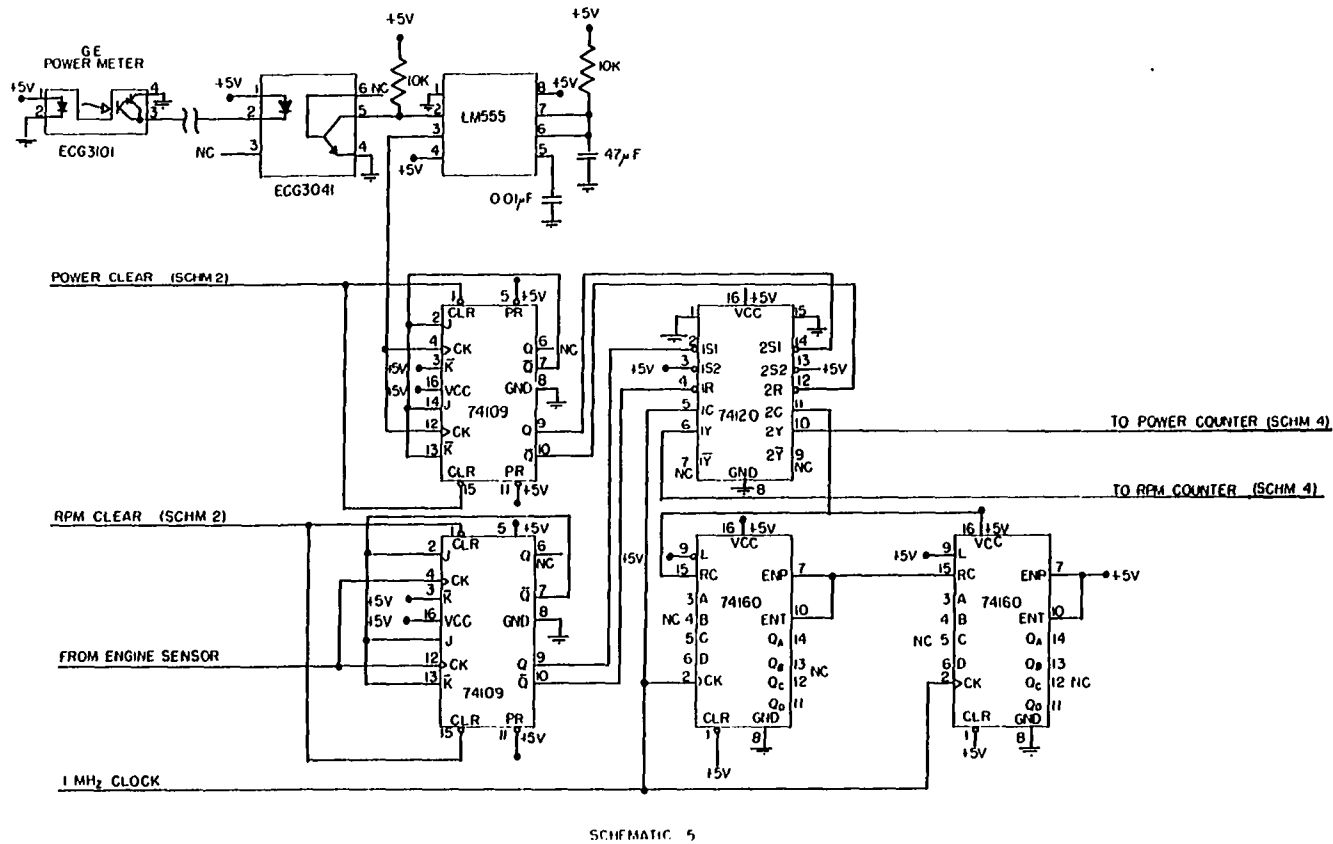


Figure 6. Power and RPM measurement

the hole to pass in the minimum power case.

If the pulses from the electric meter are counted in the same way as the pulses from the coolant flow meter, at minimum power only one pulse could be counted in 10 s. This would be inaccurately interpreted by the software. By using a longer timing period a more accurate reading can be obtained at the expense of a long delay. This problem can be solved by using the meter pulses, to stop and start a pulse train of a known period instead of counting them. This pulse train can only operate at a period that will not overflow the counters between consecutive power meter pulses. The 16 bit counters can count 65535 pulses which in 6 s would require a $65535/6 = 10922.5$ Hz pulse train. A 10000 Hz pulse train can be obtained by stepping down the 1 MHz Apple II clock with two divide by ten counters, SN74160 (Texas Instruments 1976). Figure 6 shows the complete power meter circuit including an SN74109 and an SN74120. Similar to the flow rate meter circuit, the SN74109 is triggered by the pulses from the power meter, and this in turn triggers the SN74120 that stops and starts the 10000 Hz pulse train from the two SN74160s. The SN74109 is wired to stop sending triggering signals after receiving two pulses from the power meter and is not reset until the counters are read and cleared by software.

The RPM of the engine is measured in the same way. There are two pulses per revolution of the engine that come from the opto interrupt (ECG 3101) mounted on the engine. A rotating plate attached to the engine front pulley interrupts the opto interrupt twice during one engine revolution. At a speed of 1800 RPM, these pulses have a period of $(60/1800)/2 = 0.016666$ s. Again these pulses are used to stop and start a pulse train of a known period. This time the pulse train can have a frequency of $65535/0.016666 = 3.93$ MHz. The 1 MHz Apple II clock can be used for the pulse train. Figure 6 shows the SN74109 and SN74120 used for measuring RPM.

Multiplexing

The multiplexing circuit (Figure 3) is used to read and clear all the counters, drive the stepper motor that changes the air fuel ratio, and operate the water valve that controls the engine temperature (Wall 1985). Lines PB0 - PB6 of VIA #2 are connected to a BCD to decimal decoder driver, SN74145, and a 3 to 8 line decoder multiplexer, SN74138 (Texas Instruments 1976). These devices are used to fan out the seven port B lines available so they become 16 control lines. The SN74145 has open collector outputs that can sink up to 80 mA of current, which is sufficient to

drive relays. Table 3 gives the function of each line and the addresses to be used with the POKE -14796,address command from BASIC or the STY \$C580 command in assembly language where register Y contains the address. Each meter address activates a SN74244 to read a pair of 4 bit counters. The clear address not only clears the counters, but also resets the respective SN74109 monostable.

Table 3. Multiplexing addresses

| Address | Function |
|---------|-----------------------------|
| 0 | Stepper motor relay |
| 1 | Stepper motor relay |
| 2 | Stepper motor relay |
| 3 | Stepper motor relay |
| 4 | Open coolant control valve |
| 5 | Close coolant control valve |
| 6 | LSB power meter |
| 7 | MSB power meter |
| 8 | LSB RPM counter |
| 9 | MSB RPM counter |
| 10 | No state (all outputs off) |
| 11 | No state (all outputs off) |
| 26 | LSB water meter |
| 42 | MSB water meter |
| 58 | LSB counter not used |
| 74 | MSB counter not used |
| 90 | Clear water meter counter |
| 106 | Clear RPM counter |
| 122 | Clear power meter counter |

DATA LOGGER SOFTWARE

The Apple II data logging software is written in BASIC and calls one assembly language routine that reads the counters and accesses the MicroMac-4000. The software is designed to allow a test to run for a number of minutes before a variable is changed. The engine parameters are printed and saved every minute; but the overall means and standard errors are only printed and saved at the end of each data set collection period. The number of minutes in a data set and a time delay between data sets is determined by user during start up. The time delay between data set collection periods allows the engine generator to reach steady state conditions after an operating variable has been changed. (See Table 10 for a sample printout of data.)

The MicroMac-4000 has a number of control commands (Analog Devices 1981). In this application only the ACTIVE n,m and FSCan commands are used. The ACTIVE n,m command initializes the analog channels from n to m which, in this case, is 0 to 8. After using ACTIVE n,m the FSCan command automatically reads only the activated analog channels. All the communication with the MicroMac-4000 is in ASCII code. The assembly language routine must first send the command in the format

```
*0:ATC/0/8:<cr>
```

where

<cr> = carriage return, which is ASCII code 13.

The MicroMac-4000 replies with the following:

```
*00::CS<cr><lf>
```

where

<lf> = line feed

CS = check sum which is a two digit hexadecimal value which represents the last two digits of the sum of the ASCII code for all the characters in that line.

After initialization the FSCan command is sent in the format

```
*0:FCA<cr>
```

The MicroMac replies with the following:

```
*00:+0000.0/+0000.0/+0000.0/+0000.0/+0000.0/+0000.0/
+0000.0/+0000.0:CS<cr><lf>
*00:+0000.0:CS<cr><lf>
```

The +0000.0s in the reply represent the data from the analog channels. It is to be noted that the MicroMac sends two lines of data when more than eight channels of data are requested.

Assembly language routines operate much faster than BASIC programs, so to speed up the data collection; manipulation of the MicroMac reply is handled in the assembly language routine. All the unwanted characters are

removed from the MicroMac reply, and the data are stored in a continuous chain in the Apple II memory to be read by the BASIC program. The Appendix shows the assembled listing of assembly language routine. The routine resides in the Apple II memory from \$8A00 to \$8B7E (-30464 to -29826 Apple decimal) and uses the following memory locations \$8C10 (-29680), \$8D00 (-29440) and \$8BF0 (-29712) respectively, to hold the start of MicroMac commands, data chain, and flags to signify counter data ready. The assembly language determines that the data from the power meter counter are ready by storing the counts at the beginning of the routine and then checking them again later in the routine to see if they have changed. The same count indicates that the meter has stopped and the counter can be read and cleared. The coolant flow meter is read every 10 s, timed by a clock card and checked by the assembly language routine. Flags are set each time there is power or coolant data and the BASIC software checks these flags. The RPM counters are read every time the routine is called since they are updated faster than the MicroMac can be read.

The BASIC program calls the assembly language routine (CALL -30464) and then retrieves the data from memory adding it to the previously saved data. After 1 minute the data are averaged and the individual engine parameters are

calculated, in the BASIC software, and printed. The results are saved in a pseudo RAM disk to be down loaded and saved on floppy disk at the end of each data set. To save BASIC operating time; the results are not printed on the screen, however, the data from each channel are printed directly on the screen by the assembly language routine. The one minute time interval is timed by a clock card and is checked by the assembly language routine which sets a flag at the end of each minute. About 44 sets of data are collected in 1 minute.

Calibration

At the end of each minute the data from the counters and each analog channel are averaged. These now have to be converted into meaningful numbers by the software. The counters are handled in the following manner

$$\text{RPM} = \frac{60 \times \text{HZ}}{N \times 10^{-6}}$$

where

HZ = 1.023 (frequency correction)

N = 1 MHz counts for one engine revolution.

$$\text{Power} = \frac{P \times 3600 \times \text{HZ}}{2 \times N \times 10^{-4}} = \frac{54 \times 10^6 \times \text{HZ}}{N} \quad \text{Watts}$$

where

$$P = 3 \text{ Wh/rev}$$

$$N = 10 \text{ kHz counts for half a meter disk revolution.}$$

The coolant mass flow rate assumes that 1 liter of water has a mass of 1 kilogram.

$$\text{Coolant} = N \times 6 / 52.8 = N \times 0.11355 \quad \text{kg/min}$$

where

$$N = \text{flow meter count in 10 seconds.}$$

Heat rejected in the coolant is given by

$$Q_w = m_w \times c_p \times (CH4 - CH5) W$$

where

$$m_w = \text{mass flow rate of coolant}$$

$$= .11355/60 \times N \quad \text{kg/s}$$

$$c_p = \text{specific heat capacity of water}$$

$$= 4190 \quad \text{J/kg}$$

$$CH4 = \text{MicroMac channel 4 (coolant exit temperature } ^\circ\text{C)}$$

$$CH5 = \text{MicroMac channel 5 (coolant inlet temperature } ^\circ\text{C)}$$

The gas flow rate requires calibration of the laboratory made laminar flow element. Mass flow rate of the gas is calculated assuming that the methane behaves as an ideal gas.

$$M_g = QP/R_g T_g$$

where

M_g = mass gas flow rate kg/h

Q = volumetric gas flow rate m^3/h

P = absolute gas pressure Pa

R_g = gas constant (methane) = $8.314/0.016 \text{ m}^3\text{Pa/kg-K}$

T_g = gas temperature K.

By running the engine at various loads and measuring the gas flow rate through the utility company's gas meter, an empirical equation for the gas meter can be developed. The flow rate Q is a function of pressure drop across the element and gas viscosity, which varies with temperature.

$$Q = \text{fn}(\Delta P/\mu)$$

For a temperature range of 0 to 50 C a function for viscosity can be found (Golubev 1970).

Table 4. Viscosity of methane for varying temperatures

| Temperature (C) | Viscosity (Pa.s) |
|-----------------|------------------|
| 0 | 1028E-08 |
| 20 | 1092E-08 |
| 25 | 1108E-08 |
| 50 | 1185E-08 |

Least squares fit

$$\mu = (1028.72 + 3.1379 \times T_g) \times 10^{-8}$$

Table 5 shows the results from the test. The pressure drop is expressed as a voltage read from the MicroMac-4000.

Table 5. Calibration of the gas flow element

| ΔP V | T C ^g | μ Pa.s | $\Delta P/\mu$ V/Pa.s | $m^3 Q$ /min |
|-----------------|---------------------|---------------|--------------------------|-----------------|
| 1.1788 | 36.51 | 1143.28E-08 | 1.0311E+05 | .02872 |
| 1.2448 | 35.92 | 1141.43E-08 | 1.0906E+05 | .03014 |
| 1.3049 | 36.92 | 1144.57E-08 | 1.1401E+05 | .03111 |
| 1.4952 | 36.99 | 1144.79E-08 | 1.3061E+05 | .03491 |
| 1.7302 | 37.37 | 1145.98E-08 | 1.5098E+05 | .03916 |
| 1.7850 | 37.17 | 1145.36E-08 | 1.5585E+05 | .04029 |
| 1.9807 | 37.25 | 1145.61E-08 | 1.7290E+05 | .04383 |
| 2.0342 | 36.46 | 1143.13E-08 | 1.7795E+05 | .04498 |
| 2.1231 | 36.79 | 1144.16E-08 | 1.8556E+05 | .04650 |
| 2.1304 | 37.43 | 1146.17E-08 | 1.8587E+05 | .04655 |
| 2.2156 | 37.21 | 1145.48E-08 | 1.9342E+05 | .04806 |
| 2.2530 | 37.16 | 1145.32E-08 | 1.9671E+05 | .04879 |
| 2.3915 | 37.20 | 1145.45E-08 | 2.0878E+05 | .05120 |
| 2.4762 | 34.98 | 1138.48E-08 | 2.1750E+05 | .05367 |
| 2.5611 | 36.53 | 1143.35E-08 | 2.2400E+05 | .05456 |
| 2.6818 | 34.13 | 1135.82E-08 | 2.3611E+05 | .05762 |
| 3.3648 | 36.77 | 1144.10E-08 | 2.9410E+05 | .06863 |
| 3.3543 | 32.06 | 1129.32E-08 | 2.9702E+05 | .07044 |

Figure 7 shows Q plotted against $\Delta P/\mu$.

By using a least squares fit the following equation is derived:

$$Q = 21.21134(CH1 - 0.096)/(1028.72 + 3.1379CH7) + 7.102 \times 10^{-3}$$

where

CH1 = MicroMac channel 1 (pressure drop) V

CH7 = MicroMac channel 7 (gas temperature) C.

The value 0.096 is in the equation to give a zero voltage

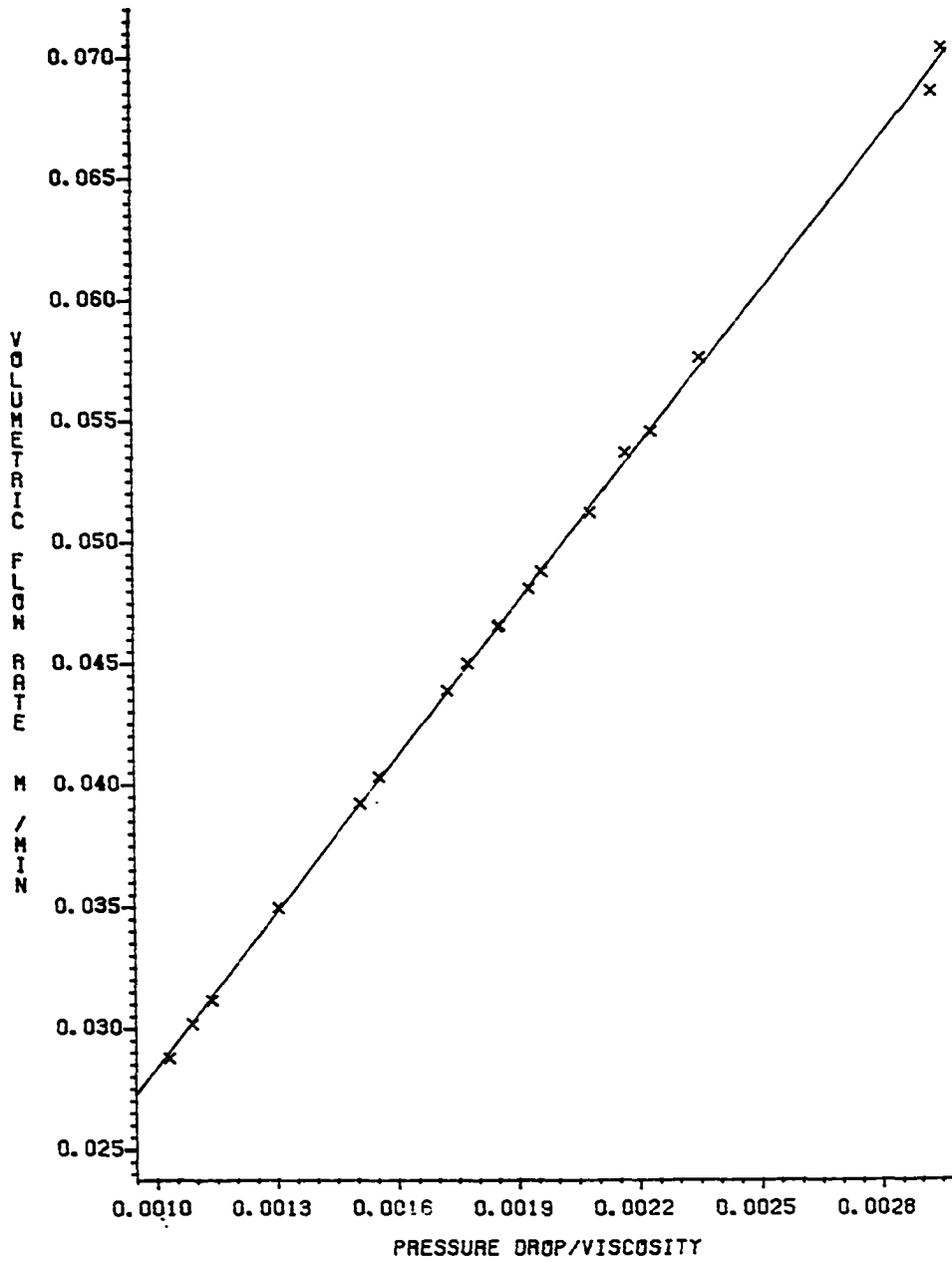


Figure 7. Volumetric gas flow vs. pressure drop divided by viscosity

reading at zero pressure drop. The equation itself does give a value when the gas is not flowing. This will not affect results since the equation is empirically derived for the operating range of the engine.

The absolute gas pressure is determined by the pressure transducer connected to channel 2 (CH2) of the MicroMac. The pressure transducer measures only the gauge pressure of the gas and the absolute pressure is found by adding the barometric pressure to the gauge pressure in the BASIC program. Table 6 shows the voltage readings from channel 2 against varying gauge pressure.

Table 6. Gauge gas pressure expressed as MicroMac-4000 voltage

| Channel 2 V | Gas pressure Pa | Channel 2 V | Gas pressure Pa |
|----------------|--------------------|----------------|--------------------|
| 0.5117 | 235 | 3.897 | 1649 |
| 1.1993 | 531 | 3.9328 | 1674 |
| 1.8394 | 800 | 3.9765 | 1684 |
| 2.5253 | 1101 | 4.0007 | 1689 |
| 3.1894 | 1370 | 4.114 | 1768 |
| 3.5462 | 1519 | 4.150 | 1756 |
| 3.7796 | 1607 | 4.47 | 1881 |
| 3.8458 | 1625 | 4.7832 | 2055 |

A least squares fit of these data gives

$$\text{Gauge pressure} = 418.42 \text{ CH2} + 28.02.$$

The actual gas pressure in pascals is given by

$$P_{\text{gas}} = P_{\text{atmos}} + 418.42 \text{ CH2} + 28.02.$$

The mass flow rate (kg/min) of gas is

$$M_g = \frac{21.2134(CH1 - 0.096)}{1028.72 + 3.1379CH7} + 7.102 \times 10^{-3}$$

$$\times \frac{(P_{atmos} + 418.42CH2 + 28.02) \times 0.016 \times 60}{(CH7 + 273.2) \times 8.314}$$

This equation is used in the BASIC program at the end of each minute. The mass air flow rate is calculated in a similar manner. This time the volumetric flow rate equation is found from calibration data supplied by Meriam Instrument Company.

$$Q_a = 0.0779 \Delta P \text{ fn}(T)$$

where

$$Q_a = \text{volumetric flow of air } m^3/\text{min}$$

$$\Delta P = \text{pressure drop across laminar element Pa}$$

$\text{fn}(T) = \text{viscosity correction as a function of temperature.}$

The viscosity function as a function of temperature is also supplied by the manufacturer in a table form. Table 7 shows viscosity correction factor as a function of temperature.

Table 7. Viscosity correction factor as a function of temperature

| Temp. C | factor | Temp. C | factor | Temp. C | factor |
|---------|---------|---------|---------|---------|---------|
| 15.6 | 1.01487 | 16.1 | 1.01336 | 16.7 | 1.01185 |
| 17.2 | 1.01035 | 17.7 | 1.00885 | 18.3 | 1.00736 |
| 18.9 | 1.00588 | 19.4 | 1.0044 | 20.0 | 1.00292 |
| 20.6 | 1.00146 | 21.1 | 1 | 21.7 | .99854 |
| 22.2 | .99709 | 22.8 | .99564 | 23.3 | .9942 |
| 23.9 | .99277 | 24.4 | .99134 | 25.0 | .98992 |
| 25.6 | .9885 | 26.1 | .98709 | 26.7 | .98568 |
| 27.2 | .98428 | 27.8 | .98288 | 28.3 | .98149 |
| 28.9 | .9801 | 29.4 | .97872 | 30.0 | .97734 |
| 30.6 | .97597 | 31.1 | .97461 | 31.7 | .97325 |
| 32.2 | .97189 | 32.8 | .97054 | 33.3 | .96919 |
| 33.9 | .96785 | 34.4 | .96651 | 35.0 | .96518 |
| 35.6 | .96386 | 36.1 | .96253 | 36.7 | .96122 |
| 37.2 | .95991 | 37.8 | .9586 | 38.3 | .95729 |
| 38.9 | .956 | 39.4 | .9547 | 40.0 | .95341 |

A least squares fit of data gives

$$fn(T) = 1.05322 - 2.508 \times 10^{-3} \times CH6$$

where

CH6 = MicroMac channel 6 measuring air temperature C.

Calibration data for the pressure transducer are given in Table 8 showing pressure as a function of voltage from channel 3 (CH3) of the MicroMac-4000.

Table 8. Air meter pressure drop expressed as MicroMac-4000 voltage

| Channel 3 V | ΔP Pa | Channel 3 V | ΔP Pa |
|----------------|------------------|----------------|------------------|
| .248 | 112 | 3.0023 | 1357 |
| .4233 | 192 | 3.2502 | 1470 |
| .7353 | 336 | 3.6536 | 1656 |
| 1.1595 | 526 | 3.8058 | 1726 |
| 1.5875 | 717 | 4.0988 | 1861 |
| 2.0 | 897 | 4.3287 | 1973 |
| 2.3938 | 1081 | 4.7309 | 2152 |
| 2.7963 | 1268 | 4.9544 | 2254 |

A least squares fit gives the following equation

$$\Delta P = 454.97 \text{ CH3} - 3.89.$$

To calculate the mass flow rate of air, the absolute pressure of the air entering the flow meter must be known. The engine air filter is placed up stream of the flow element to protect it and the engine from dust. There is a pressure drop across the filter which needs to be accounted for. This drop is also determined by the voltage on channel 3 of the MicroMac. By measuring the pressure drop across the filter for different flow rates, the following Table of voltage on channel 3 versus pressure drop is developed.

Table 9. Pressure drop versus channel 3 voltage for the engine air filter

| Channel 3 V | ΔP_{filter} Pa | Channel 3 V | ΔP_{filter} Pa |
|----------------|----------------------------------|----------------|----------------------------------|
| 1.9327 | 199.3 | 3.1539 | 373.6 |
| 2.1348 | 224.2 | 3.752 | 473.3 |
| 2.4579 | 274.0 | 4.5488 | 622.7 |
| 2.7608 | 311.6 | | |

A least squares fit gives the following polynomial:

$$\Delta P_{\text{filter}} = 7.372 + 73.178CH3 + 13.634CH3^2.$$

The humidity will also affect the absolute pressure of air entering the engine. When the humidity is known, a correction for the water vapor pressure is made with the following equation (Jones and Hawkins 1960):

$$P_{\text{air}} = p_m - \phi p_v(T)$$

where

P_{air} = dry air pressure Pa

p_m = measured pressure Pa

ϕ = relative humidity

$p_v(T)$ = vapor pressure as a function of temperature Pa.

Steam Tables (Keenan et al. 1969) give vapor pressures versus temperature and for the range of 15 to 38 C the following least squares fit for the data is obtained:

$$p_v(T) = 167.93 - 7.522CH6 + 0.5472CH6^2$$

By substituting all the above equations into the mass flow rate equation

$$M_{\text{air}} = Q_a P_a / R_a T_a$$

where

P_a = air pressure entering the laminar element Pa

T_a = air temperature C

R_a = gas constant (air) $8.314/28.96 \text{ m}^3\text{-Pa/kg-K}$

the following empirical equation is found

$$M_{\text{air}} = (0.0779 \times (454.97\text{CH}_3 - 3.89) \times (1.05322 - 2.508 \times 10^{-3}\text{CH}_6) \times (P_{\text{atmos}} - \Phi \times (167.93 - 7.522\text{CH}_6 + 0.5472\text{CH}_6^2) - 7.372 + 73.178\text{CH}_3 + 3.634\text{CH}_3^2)) / (0.2871 \times (273.3 + \text{CH}_6)).$$

This equation is also used in the BASIC program once every minute. The air fuel ratio is calculated by dividing the mass gas flow rate by the mass air flow rate. The other calculations made by the software are to average the voltage produced by the oxygen sensor and average the engine exhaust temperature.

Propagated standard deviation

To check the variation of each result the propagated standard deviation is calculated. During the data collection process the sums of the results and the sums of the squares from each MicroMac channel and counter are saved in a software array. At the end of each data collection period the standard deviation for each channel and counter

is calculated using the following equation (Chatfield 1978)

$$s^2 = \frac{S - nM^2}{(n-1)}$$

where

s = standard deviation

S = sum of the squares

M = sample mean

n = number of points in sample.

These results are then transformed to propagated standard deviations of each of the computed results by using the following equation (Topping 1972)

$$s.e.^2 = \frac{\partial f^2}{\partial m_1} s_1^2 + \frac{\partial f^2}{\partial m_2} s_2^2 + \frac{\partial f^2}{\partial m_3} s_3^2 + \dots$$

where

s.e. = propagated standard deviation of the function

f = function = $f(m_1, m_2, m_3, \dots)$

m_1, m_2, m_3 = means of variables in the function

s_1, s_2, s_3 = standard deviations of the variables.

For example, the propagated standard deviation of the heat rejected in the coolant is found in the following way. Heat rejected in the coolant is given by

$$Q_w = m_w \times c_p \times (CH4 - CH5)$$

then

$$\frac{\partial Q_w}{\partial m_w} = c_p \times (CH4 - CH5)$$

$$\frac{\partial Q_w}{\partial CH4} = m_w \times c_p$$

$$\frac{\partial Q_w}{\partial CH5} = - m_w \times c_p$$

and the propagated standard deviation is given by

$$(s.e.Q_w)^2 = c_p^2 \times ((CH4-CH5)^2 \times (sm_w)^2 + m_w^2 \times (s_{CH4}^2 + s_{CH5}^2))$$

where

m_w = mass flow rate of coolant

$$= .11355/60 \times N \quad \text{kg/s}$$

c_p = specific heat capacity of water

$$= 4190 \quad \text{J/kg}$$

CH4= MicroMac channel 4 (coolant exit temperature C)

CH5= MicroMac channel 5 (coolant inlet temperature C)

sm_w = standard deviation of the coolant flow rate

s_{CH4} = standard deviation of MicroMac channel 4

s_{CH5} = standard deviation of MicroMac channel 5.

The equations used in the software to calculate the other propagated standard deviations are not listed here because the interrelation of the variables make the mass air

flow and mass gas flow standard error equations long and complicated. The standard errors are calculated for all the data collected in the collection period and not just the averages of each minute of data. It must be noted that the propagated standard deviation is only an indication of the variation in measurements and not total error. The difference between actual and measured results is not indicated.

RESULTS AND DISCUSSION

Table 10 shows a printout of one set of data collected. The air fuel ratio is the engine variable changing. The data collection period is 5 minutes with a 6 minute delay between data sets. These two time periods worked well for small changes of engine parameters. The standard errors on the results indicate errors of less than 1% with the exception of the coolant heat rejection and mass flow rate of coolant. At times when the engine is running smoothly, the coefficient of variation (propagated standard deviation/mean) for most of the results are less than 0.5%.

The coolant errors are larger because of the inadequate flow meter. The flow meter is operating on the low limit of the meter range and is producing too few pulses in a 10 second period for accurate results. Replacing the Kent meter with a flow meter more suited to the flow rates and with a larger number of pulses per liter would allow better coolant data to be obtained.

The data tabulated are the averages of about 44 sets of data a minute. With a faster computer or software the MicroMac is capable of reading an analog sensor faster than

twice a second. This would enable dynamic tests to be performed on the engine generator set and the development of a control system to handle large sudden changes in power requirements.

Figures 8 to 11 show the data graphically. With the exception of the coolant heat rejection curve the graphs show that the data logger and instrumentation provide smooth and consistent curves.

Table 10. Data collected by the data logger and instrumentation^a

| Time | RPM | Power ^b W | Q_w^c W | m_w^d kg/m | T_w^e C | T_a^f C | M_{air}^g kg/h | M_{gas}^h kg/h | A/R ⁱ | O_2^j mV | T_e^k C |
|---------------------|------|-------------------------|--------------|-----------------|--------------|--------------|---------------------|---------------------|------------------|---------------|--------------|
| 15;07 | 1812 | 5000 | 11414 | 2.385 | 85.14 | 28.9 | 37.12 | 2.498 | 14.861 | 918 | 355 |
| 15;08 | 1812 | 5001 | 10910 | 2.271 | 85.39 | 28.5 | 37.13 | 2.497 | 14.871 | 918 | 355 |
| 15;09 | 1813 | 4998 | 11474 | 2.385 | 85.50 | 28.7 | 37.14 | 2.501 | 14.849 | 918 | 355 |
| 15;10 | 1812 | 4997 | 11468 | 2.385 | 85.46 | 29.7 | 37.04 | 2.499 | 14.818 | 918 | 355 |
| 15;11 | 1812 | 4996 | 11467 | 2.385 | 85.46 | 29.5 | 37.09 | 2.502 | 14.825 | 918 | 356 |
| Mean | 1812 | 4999 | 11350 | 2.362 | 85.39 | 29.1 | 37.11 | 2.500 | 14.845 | 918 | 355 |
| ^l P.s.d. | 4.27 | 9.96 | 245 | .0508 | 0.162 | 0.52 | 0.199 | .0100 | .09940 | 0.5 | .43 |

^aSpark advance before top dead center = 32.4 degrees

^bPower = generator power

^c Q_w = coolant heat rejection

^d m_w = coolant flow rate

^e T_w = coolant exit temperature

^f T_a = air temperature

^g M_{air} = mass flow rate of air

^h M_{gas} = mass flow rate of gas

ⁱA/R = Air fuel ratio

^j O_2 = oxygen sensor voltage

^k T_e = exhaust gas temperature

^lP.s.d. = propagated standard deviation

Table 10. continued

| Time | RPM | Power W | Q _w W | m _w kg/m | T _w C | T _a C | M _{air} kg/h | M _{gas} kg/h | A/R | O ₂ mv | T _e C |
|--------|------|------------|---------------------|------------------------|---------------------|---------------------|--------------------------|--------------------------|--------|----------------------|---------------------|
| 15;31 | 1814 | 4999 | 11538 | 2.385 | 85.79 | 26.9 | 37.12 | 2.463 | 15.070 | 912 | 356 |
| 15;32 | 1814 | 5000 | 10978 | 2.271 | 85.72 | 27.1 | 37.12 | 2.461 | 15.082 | 912 | 356 |
| 15;33 | 1814 | 5003 | 10940 | 2.271 | 85.48 | 26.0 | 37.19 | 2.460 | 15.116 | 912 | 356 |
| 15;34 | 1814 | 5000 | 10910 | 2.271 | 85.29 | 26.1 | 37.22 | 2.461 | 15.121 | 912 | 356 |
| 15;35 | 1814 | 4998 | 12000 | 2.498 | 85.21 | 26.3 | 37.19 | 2.461 | 15.111 | 912 | 356 |
| Mean | 1814 | 5000 | 11270 | 2.339 | 85.50 | 26.5 | 37.17 | 2.461 | 15.100 | 912 | 356 |
| P.s.d. | 3.99 | 10.25 | 491 | .1016 | 0.246 | 0.48 | 0.170 | .0094 | .08995 | 0.4 | .41 |
| 15;42 | 1813 | 5007 | 11604 | 2.385 | 86.10 | 25.2 | 37.35 | 2.437 | 15.323 | 908 | 357 |
| 15;47 | 1812 | 5018 | 11506 | 2.385 | 85.50 | 24.5 | 37.43 | 2.436 | 15.368 | 908 | 357 |
| 15;48 | 1813 | 5015 | 12057 | 2.498 | 85.50 | 24.4 | 37.43 | 2.437 | 15.361 | 908 | 357 |
| 15;49 | 1814 | 5005 | 11486 | 2.385 | 85.37 | 25.7 | 37.20 | 2.436 | 15.272 | 908 | 357 |
| 15;50 | 1815 | 5003 | 10935 | 2.271 | 85.35 | 25.1 | 37.29 | 2.435 | 15.312 | 908 | 357 |
| Mean | 1813 | 5010 | 11520 | 2.385 | 85.57 | 25.0 | 37.34 | 2.436 | 15.328 | 908 | 357 |
| P.s.d. | 4.42 | 12.26 | 391 | .0803 | 0.294 | 0.55 | 0.194 | .0100 | .10120 | 0.5 | .28 |

Table 10. continued

| Time | RPM | power W | Q _w W | m _w kg/m | T _w C | T _a C | M _{air} kg/h | M _{gas} kg/h | A/F | O ₂ mv | T _e C |
|--------|------|------------|---------------------|------------------------|---------------------|---------------------|--------------------------|--------------------------|--------|----------------------|---------------------|
| 16;07 | 1813 | 5000 | 11960 | 2.498 | 84.96 | 26.0 | 37.36 | 2.393 | 15.610 | 903 | 359 |
| 16;08 | 1814 | 4997 | 11949 | 2.498 | 84.89 | 26.1 | 37.36 | 2.393 | 15.608 | 903 | 359 |
| 16;09 | 1814 | 5004 | 11917 | 2.498 | 84.71 | 25.2 | 37.41 | 2.390 | 15.654 | 903 | 359 |
| 16;10 | 1812 | 4998 | 12417 | 2.612 | 84.48 | 25.6 | 37.42 | 2.391 | 15.648 | 903 | 358 |
| 16;11 | 1813 | 5001 | 11325 | 2.385 | 84.40 | 24.7 | 37.47 | 2.389 | 15.681 | 903 | 358 |
| Mean | 1813 | 5000 | 11910 | 2.498 | 84.69 | 25.5 | 37.40 | 2.391 | 15.640 | 903 | 359 |
| P.s.d. | 3.57 | 11.32 | 385 | .0803 | 0.232 | 0.60 | 0.201 | .0081 | .09935 | 0.9 | .49 |
| 16;18 | 1811 | 5005 | 12034 | 2.498 | 85.36 | 25.2 | 37.48 | 2.323 | 16.136 | 896 | 359 |
| 16;19 | 1813 | 5001 | 12052 | 2.498 | 85.48 | 25.2 | 37.46 | 2.322 | 16.131 | 895 | 360 |
| 16;20 | 1812 | 5000 | 12593 | 2.612 | 85.42 | 24.9 | 37.47 | 2.321 | 16.146 | 895 | 361 |
| 16;21 | 1812 | 5005 | 11485 | 2.385 | 85.32 | 25.4 | 37.50 | 2.324 | 16.134 | 896 | 361 |
| 16;22 | 1812 | 5002 | 11518 | 2.385 | 85.48 | 26.7 | 37.35 | 2.324 | 16.070 | 896 | 361 |
| Mean | 1812 | 5003 | 11940 | 2.475 | 85.41 | 25.5 | 37.45 | 2.323 | 16.124 | 896 | 360 |
| P.s.d. | 3.62 | 9.91 | 459 | .0950 | 0.117 | 0.67 | 0.205 | .0087 | .10718 | 0.6 | .70 |

Table 10. continued

| Time | RPM | power W | Q _w W | m _w kg/m | T _w C | T _a C | M _{air} kg/h | M _{gas} kg/h | A/F | O ₂ mv | T _e C |
|--------|------|------------|---------------------|------------------------|---------------------|---------------------|--------------------------|--------------------------|--------|----------------------|---------------------|
| 16;33 | 1811 | 5012 | 11980 | 2.498 | 85.07 | 26.1 | 37.51 | 2.299 | 16.318 | 891 | 361 |
| 16;34 | 1812 | 5006 | 12002 | 2.498 | 85.20 | 25.8 | 37.43 | 2.296 | 16.304 | 891 | 362 |
| 16;35 | 1812 | 5012 | 12532 | 2.612 | 85.11 | 24.8 | 37.52 | 2.292 | 16.372 | 890 | 361 |
| 16;36 | 1816 | 5014 | 11436 | 2.385 | 85.07 | 24.4 | 37.45 | 2.292 | 16.339 | 891 | 362 |
| 16;37 | 1815 | 5013 | 11421 | 2.385 | 84.97 | 25.3 | 37.42 | 2.296 | 16.301 | 891 | 362 |
| Mean | 1813 | 5011 | 11870 | 2.475 | 85.09 | 25.3 | 37.47 | 2.295 | 16.327 | 891 | 362 |
| P.s.d. | 4.16 | 10.94 | 456 | .0950 | 0.098 | 0.67 | 0.241 | .0081 | .11996 | 0.7 | .50 |
| 16;44 | 1813 | 5003 | 12018 | 2.498 | 85.29 | 25.5 | 37.48 | 2.249 | 16.666 | 883 | 363 |
| 16;45 | 1815 | 5007 | 12571 | 2.612 | 85.33 | 25.0 | 37.42 | 2.245 | 16.667 | 882 | 363 |
| 16;46 | 1814 | 4992 | 12038 | 2.498 | 85.39 | 25.1 | 37.47 | 2.248 | 16.671 | 883 | 363 |
| 16;47 | 1814 | 4987 | 11498 | 2.385 | 85.44 | 25.5 | 37.38 | 2.248 | 16.633 | 883 | 364 |
| 16;48 | 1811 | 5012 | 11527 | 2.385 | 85.62 | 25.1 | 37.52 | 2.252 | 16.662 | 882 | 364 |
| Mean | 1814 | 5000 | 11930 | 2.475 | 85.41 | 25.2 | 37.45 | 2.248 | 16.660 | 883 | 363 |
| P.s.d. | 4.65 | 13.74 | 459 | .0950 | 0.161 | 0.39 | 0.172 | .0072 | .09351 | 1.2 | .54 |

Table 10. continued

| Time | RPM | power W | Q _w W | m _w kg/m | T _w C | T _a C | M _{air} kg/h | M _{gas} kg/h | A/F | O ₂ mv | T _e C |
|--------|------|------------|---------------------|------------------------|---------------------|---------------------|--------------------------|--------------------------|--------|----------------------|---------------------|
| 17;04 | 1812 | 5014 | 12630 | 2.612 | 85.55 | 24.6 | 37.52 | 2.204 | 17.025 | 866 | 366 |
| 17;05 | 1814 | 5011 | 12088 | 2.498 | 85.58 | 25.1 | 37.44 | 2.205 | 16.976 | 868 | 366 |
| 17;06 | 1813 | 5007 | 12049 | 2.498 | 85.37 | 25.1 | 37.51 | 2.206 | 17.005 | 868 | 365 |
| 17;07 | 1812 | 4992 | 11499 | 2.385 | 85.35 | 27.2 | 37.39 | 2.212 | 16.908 | 870 | 366 |
| 17;08 | 1810 | 4987 | 12613 | 2.612 | 85.46 | 29.1 | 37.30 | 2.215 | 16.841 | 872 | 366 |
| Mean | 1812 | 5002 | 12180 | 2.521 | 85.46 | 26.2 | 37.44 | 2.208 | 16.952 | 869 | 366 |
| P.s.d. | 4.41 | 15.21 | 460 | .0950 | 0.158 | 1.72 | 0.499 | .0078 | .23359 | 2.4 | .37 |
| 17;19 | 1810 | 4990 | 12557 | 2.612 | 85.25 | 30.7 | 37.35 | 2.174 | 17.178 | 859 | 367 |
| 17;20 | 1810 | 4986 | 12608 | 2.612 | 85.53 | 30.4 | 37.39 | 2.172 | 17.217 | 859 | 367 |
| 17;21 | 1808 | 4988 | 11528 | 2.385 | 85.63 | 30.7 | 37.42 | 2.174 | 17.210 | 859 | 367 |
| 17;22 | 1808 | 4988 | 12646 | 2.612 | 85.74 | 30.7 | 37.40 | 2.174 | 17.205 | 859 | 367 |
| 17;23 | 1810 | 4987 | 12606 | 2.612 | 85.52 | 30.2 | 37.43 | 2.173 | 17.228 | 860 | 367 |
| Mean | 1809 | 4988 | 12390 | 2.566 | 85.53 | 30.5 | 37.40 | 2.173 | 17.207 | 859 | 367 |
| P.s.d. | 4.15 | 11.01 | 492 | .1016 | 0.194 | 0.24 | 0.124 | .0065 | .07719 | 1.6 | .12 |

Table 10. continued

| Time | RPM | power W | Q_w W | m_w kg/m | T_w C | T_a C | M_{air} kg/h | M_{gas} kg/h | A/F | O ₂ mv | T_e C |
|--------|------|------------|------------|---------------|------------|------------|-------------------|-------------------|--------|----------------------|------------|
| 17;52 | 1810 | 4987 | 12593 | 2.612 | 85.50 | 31.5 | 37.35 | 2.151 | 17.369 | 850 | 368 |
| 17;53 | 1812 | 4988 | 12579 | 2.612 | 85.47 | 31.6 | 37.31 | 2.150 | 17.356 | 849 | 368 |
| 17;54 | 1810 | 4989 | 12553 | 2.612 | 85.33 | 31.7 | 37.35 | 2.150 | 17.371 | 848 | 368 |
| 17;55 | 1812 | 4987 | 12590 | 2.612 | 85.53 | 31.7 | 37.27 | 2.149 | 17.343 | 850 | 368 |
| 17;56 | 1810 | 4988 | 12033 | 2.498 | 85.48 | 31.6 | 37.32 | 2.150 | 17.361 | 850 | 368 |
| Mean | 1811 | 4988 | 12470 | 2.589 | 85.46 | 31.6 | 37.32 | 2.150 | 17.360 | 849 | 368 |
| P.s.d. | 3.80 | 10.25 | 247 | .0508 | 0.167 | 0.14 | 0.105 | .0070 | .07457 | 2.0 | .23 |
| 18;16 | 1810 | 4986 | 12455 | 2.612 | 84.79 | 32.0 | 37.28 | 2.131 | 17.498 | 829 | 369 |
| 18;17 | 1810 | 4982 | 12962 | 2.725 | 84.61 | 32.0 | 37.27 | 2.132 | 17.483 | 829 | 369 |
| 18;18 | 1809 | 4983 | 11865 | 2.498 | 84.51 | 31.9 | 37.28 | 2.132 | 17.487 | 827 | 369 |
| 18;19 | 1809 | 4976 | 12397 | 2.612 | 84.47 | 31.7 | 37.34 | 2.132 | 17.510 | 824 | 369 |
| 18;20 | 1808 | 4978 | 12405 | 2.612 | 84.52 | 31.8 | 37.38 | 2.133 | 17.524 | 826 | 369 |
| Mean | 1809 | 4981 | 12420 | 2.612 | 84.58 | 31.9 | 37.31 | 2.132 | 17.500 | 827 | 369 |
| P.s.d. | 3.26 | 11.58 | 383 | .0803 | 0.148 | 0.19 | 0.104 | .0064 | .07159 | 3.4 | .33 |

Table 10. continued

| Time | RPM | power W | Q_w W | m_w kg/m | T_w C | T_a C | M_{air} kg/h | M_{gas} kg/h | A/F | O_2 mv | T_e C |
|--------|------|------------|------------|---------------|------------|------------|-------------------|-------------------|--------|-------------|------------|
| 18;41 | 1810 | 4984 | 12956 | 2.725 | 84.58 | 32.2 | 37.41 | 2.113 | 17.702 | 759 | 370 |
| 18;42 | 1808 | 4987 | 12910 | 2.725 | 84.33 | 31.5 | 37.50 | 2.112 | 17.755 | 747 | 370 |
| 18;43 | 1809 | 4992 | 11820 | 2.498 | 84.26 | 31.8 | 37.45 | 2.112 | 17.733 | 758 | 370 |
| 18;44 | 1807 | 4980 | 12367 | 2.612 | 84.31 | 31.8 | 37.46 | 2.112 | 17.738 | 753 | 370 |
| 18;45 | 1810 | 4969 | 12388 | 2.612 | 84.42 | 32.1 | 37.42 | 2.112 | 17.718 | 770 | 370 |
| Mean | 1809 | 4982 | 12490 | 2.634 | 84.38 | 31.9 | 37.45 | 2.112 | 17.728 | 757 | 370 |
| P.s.d. | 3.97 | 12.92 | 451 | .0950 | 0.146 | 0.28 | 0.120 | .0061 | .07668 | 12.3 | .45 |
| 19;09 | 1807 | 4988 | 12615 | 2.612 | 85.70 | 32.1 | 37.62 | 2.100 | 17.920 | 648 | 373 |
| 19;10 | 1809 | 4982 | 12594 | 2.612 | 85.57 | 32.0 | 37.58 | 2.097 | 17.917 | 660 | 372 |
| 19;11 | 1809 | 4984 | 12057 | 2.498 | 85.62 | 32.2 | 37.54 | 2.098 | 17.889 | 655 | 372 |
| 19;12 | 1809 | 4986 | 12075 | 2.498 | 85.72 | 31.9 | 37.58 | 2.096 | 17.925 | 649 | 372 |
| 19;13 | 1807 | 4986 | 13130 | 2.725 | 85.52 | 31.8 | 37.65 | 2.097 | 17.949 | 643 | 372 |
| Mean | 1808 | 4985 | 12490 | 2.589 | 85.63 | 32.0 | 37.59 | 2.098 | 17.920 | 651 | 372 |
| P.s.d. | 3.43 | 9.74 | 459 | .0950 | 0.116 | 0.24 | 0.118 | .0060 | .07581 | 9.7 | .46 |

Table 10. continued

| Time | RPM | power W | Q _w W | m _w kg/m | T _w C | T _a C | M _{air} kg/h | M _{gas} kg/h | A/F | O ₂ mv | T _e C |
|--------|------|------------|---------------------|------------------------|---------------------|---------------------|--------------------------|--------------------------|--------|----------------------|---------------------|
| 19;38 | 1805 | 4974 | 13110 | 2.725 | 85.49 | 32.5 | 37.83 | 2.082 | 18.172 | 171 | 373 |
| 19;39 | 1806 | 4978 | 12551 | 2.612 | 85.42 | 32.2 | 37.82 | 2.081 | 18.175 | 186 | 373 |
| 19;40 | 1807 | 4972 | 12046 | 2.498 | 85.65 | 32.2 | 37.81 | 2.081 | 18.172 | 315 | 373 |
| 19;41 | 1808 | 4980 | 12084 | 2.498 | 85.87 | 32.1 | 37.75 | 2.078 | 18.163 | 389 | 373 |
| 19;42 | 1809 | 4976 | 12073 | 2.498 | 85.81 | 32.2 | 37.70 | 2.077 | 18.148 | 419 | 373 |
| Mean | 1807 | 4976 | 12370 | 2.566 | 85.65 | 32.2 | 37.78 | 2.080 | 18.166 | 293 | 373 |
| P.s.d. | 4.20 | 11.12 | 491 | .1016 | 0.204 | 0.17 | 0.134 | .0061 | .08330 | 108.3 | .16 |
| 20;10 | 1805 | 4973 | 12575 | 2.612 | 85.60 | 31.8 | 38.00 | 2.067 | 18.387 | 88 | 373 |
| 20;11 | 1806 | 4970 | 13133 | 2.725 | 85.66 | 31.8 | 37.97 | 2.067 | 18.369 | 87 | 373 |
| 20;12 | 1806 | 4965 | 13098 | 2.725 | 85.48 | 32.0 | 37.93 | 2.066 | 18.361 | 89 | 372 |
| 20;13 | 1805 | 4969 | 12491 | 2.612 | 85.16 | 32.1 | 37.93 | 2.067 | 18.348 | 88 | 373 |
| 20;14 | 1806 | 4962 | 11959 | 2.498 | 85.23 | 32.2 | 37.89 | 2.067 | 18.331 | 88 | 373 |
| Mean | 1806 | 4968 | 12650 | 2.634 | 85.43 | 32.0 | 37.95 | 2.067 | 18.360 | 88 | 373 |
| P.s.d. | 3.13 | 11.64 | 458 | .0950 | 0.233 | 0.18 | 0.113 | .0062 | .07746 | 1.7 | .36 |

Table 10. continued

| Time | RPM | power W | Q_w W | m_w kg/m | T_w C | T_a C | M_{air} kg/h | M_{gas} kg/h | A/F | O ₂ mv | T_e C |
|--------|------|------------|------------|---------------|------------|------------|-------------------|-------------------|--------|----------------------|------------|
| 20;40 | 1803 | 4980 | 12531 | 2.612 | 85.40 | 33.3 | 38.26 | 2.053 | 18.634 | 73 | 372 |
| 20;41 | 1802 | 4979 | 12459 | 2.612 | 85.01 | 33.4 | 38.28 | 2.054 | 18.642 | 73 | 372 |
| 20;42 | 1801 | 4977 | 12965 | 2.725 | 84.83 | 33.2 | 38.33 | 2.055 | 18.650 | 71 | 372 |
| 20;43 | 1799 | 4981 | 12373 | 2.612 | 84.54 | 33.1 | 38.36 | 2.055 | 18.661 | 71 | 372 |
| 20;44 | 1799 | 4984 | 11289 | 2.385 | 84.50 | 33.1 | 38.34 | 2.055 | 18.661 | 70 | 372 |
| Mean | 1801 | 4980 | 12320 | 2.589 | 84.87 | 33.2 | 38.31 | 2.054 | 18.649 | 72 | 372 |
| P.s.d. | 3.87 | 11.06 | 596 | .1244 | 0.351 | 0.21 | 0.116 | .0061 | .07946 | 1.0 | .32 |
| 20;51 | 1800 | 4991 | 12349 | 2.612 | 84.41 | 32.2 | 38.77 | 2.048 | 18.926 | 65 | 371 |
| 20;52 | 1799 | 4986 | 12871 | 2.725 | 84.33 | 32.7 | 38.62 | 2.047 | 18.861 | 65 | 371 |
| 20;53 | 1800 | 4988 | 12330 | 2.612 | 84.30 | 32.7 | 38.71 | 2.048 | 18.900 | 66 | 371 |
| 20;54 | 1800 | 4985 | 12338 | 2.612 | 84.35 | 32.8 | 38.63 | 2.047 | 18.873 | 66 | 371 |
| 20;55 | 1798 | 4985 | 11794 | 2.498 | 84.30 | 32.6 | 38.73 | 2.047 | 18.920 | 65 | 371 |
| Mean | 1799 | 4987 | 12340 | 2.612 | 84.34 | 32.6 | 38.69 | 2.048 | 18.896 | 66 | 371 |
| P.s.d. | 3.08 | 10.32 | 380 | .0803 | 0.075 | 0.37 | 0.139 | .0058 | .08603 | 0.6 | .37 |

Table 10. continued

| Time | RPM | power W | Q _w W | m _w kg/m | T _w C | T _a C | M _{air} kg/h | M _{gas} kg/h | A/F | O ₂ mv | T _e C |
|--------|------|------------|---------------------|------------------------|---------------------|---------------------|--------------------------|--------------------------|--------|----------------------|---------------------|
| 21;03 | 1795 | 4979 | 11941 | 2.498 | 85.15 | 32.6 | 39.21 | 2.035 | 19.265 | 59 | 369 |
| 21;04 | 1795 | 4980 | 12506 | 2.612 | 85.33 | 32.6 | 39.29 | 2.035 | 19.304 | 60 | 369 |
| 21;05 | 1797 | 4983 | 11921 | 2.498 | 85.11 | 32.8 | 39.22 | 2.034 | 19.280 | 59 | 369 |
| 21;06 | 1797 | 4975 | 11926 | 2.498 | 85.10 | 32.7 | 39.26 | 2.035 | 19.291 | 59 | 369 |
| 21;07 | 1798 | 4979 | 11406 | 2.385 | 85.21 | 32.8 | 39.20 | 2.035 | 19.261 | 59 | 369 |
| Mean | 1796 | 4979 | 11940 | 2.498 | 85.18 | 32.7 | 39.24 | 2.035 | 19.280 | 59 | 369 |
| P.s.d. | 3.15 | 10.51 | 385 | .0803 | 0.133 | 0.17 | 0.131 | .0057 | .08362 | 0.5 | .47 |
| 21;14 | 1793 | 4981 | 12017 | 2.498 | 85.68 | 32.8 | 39.47 | 2.027 | 19.472 | 56 | 368 |
| 21;15 | 1794 | 4976 | 12029 | 2.498 | 85.75 | 32.9 | 39.45 | 2.027 | 19.463 | 57 | 368 |
| 21;16 | 1794 | 4972 | 12000 | 2.498 | 85.59 | 32.7 | 39.49 | 2.028 | 19.475 | 56 | 368 |
| 21;17 | 1793 | 4969 | 12462 | 2.612 | 85.10 | 32.7 | 39.55 | 2.029 | 19.493 | 56 | 368 |
| 21;18 | 1794 | 4969 | 12437 | 2.612 | 84.93 | 32.4 | 39.61 | 2.028 | 19.527 | 56 | 368 |
| Mean | 1794 | 4974 | 12190 | 2.544 | 85.41 | 32.7 | 39.51 | 2.028 | 19.486 | 56 | 368 |
| P.s.d. | 2.95 | 10.92 | 304 | .0622 | 0.338 | 0.22 | 0.120 | .0055 | .07954 | 0.4 | .26 |

Table 10. continued

| Time | RPM | power W | Q_w W | m_w kg/m | T_w C | T_a C | M_{air} kg/h | M_{gas} kg/h | A/F | O_2 mv | T_e C |
|--------|------|------------|------------|---------------|------------|------------|-------------------|-------------------|--------|-------------|------------|
| 21;25 | 1788 | 4973 | 12319 | 2.612 | 84.24 | 33.1 | 40.24 | 2.018 | 19.944 | 52 | 367 |
| 21;26 | 1790 | 4973 | 11247 | 2.385 | 84.24 | 33.2 | 40.17 | 2.016 | 19.923 | 53 | 367 |
| 21;27 | 1790 | 4970 | 11230 | 2.385 | 84.14 | 33.1 | 40.19 | 2.017 | 19.923 | 53 | 367 |
| 21;28 | 1790 | 4972 | 11763 | 2.498 | 84.13 | 33.4 | 40.14 | 2.016 | 19.909 | 53 | 366 |
| 21;29 | 1789 | 4970 | 12292 | 2.612 | 84.12 | 33.4 | 40.14 | 2.016 | 19.913 | 52 | 367 |
| Mean | 1790 | 4972 | 11770 | 2.498 | 84.18 | 33.3 | 40.18 | 2.017 | 19.923 | 53 | 367 |
| P.s.d. | 3.74 | 10.60 | 535 | .1135 | 0.090 | 0.16 | 0.136 | .0055 | .08641 | 0.9 | .41 |
| 21;40 | 1787 | 4967 | 12319 | 2.612 | 84.30 | 33.7 | 40.49 | 2.008 | 20.161 | 51 | 366 |
| 21;41 | 1787 | 4971 | 12314 | 2.612 | 84.28 | 33.6 | 40.55 | 2.009 | 20.189 | 50 | 366 |
| 21;42 | 1787 | 4963 | 12309 | 2.612 | 84.27 | 33.8 | 40.55 | 2.009 | 20.183 | 51 | 366 |
| 21;43 | 1787 | 4969 | 11778 | 2.498 | 84.30 | 34.1 | 40.53 | 2.009 | 20.176 | 50 | 366 |
| 21;44 | 1788 | 4966 | 11231 | 2.385 | 84.20 | 34.1 | 40.44 | 2.009 | 20.130 | 51 | 366 |
| Mean | 1787 | 4967 | 11990 | 2.544 | 84.27 | 33.8 | 40.51 | 2.009 | 20.168 | 51 | 366 |
| P.s.d. | 3.65 | 10.04 | 479 | .1016 | 0.067 | 0.24 | 0.149 | .0061 | .09635 | 0.5 | .38 |

Table 10. continued

| Time | RPM | power W | Q_w W | m_w kg/m | T_w C | T_a C | M_{air} kg/h | M_{gas} kg/h | A/F | O_2 mv | T_e C |
|--------|------|------------|------------|---------------|------------|------------|-------------------|-------------------|--------|-------------|------------|
| 21;56 | 1785 | 4976 | 11767 | 2.498 | 84.25 | 33.7 | 41.01 | 1.995 | 20.554 | 48 | 363 |
| 21;57 | 1786 | 4975 | 11742 | 2.498 | 84.10 | 33.7 | 41.01 | 1.996 | 20.543 | 48 | 363 |
| 21;58 | 1787 | 4978 | 12250 | 2.612 | 83.97 | 33.5 | 41.03 | 1.996 | 20.560 | 48 | 363 |
| 22;03 | 1788 | 4978 | 12316 | 2.612 | 84.23 | 33.4 | 40.95 | 1.996 | 20.516 | 47 | 363 |
| 22;04 | 1784 | 4977 | 11786 | 2.498 | 84.27 | 33.2 | 41.04 | 1.994 | 20.586 | 47 | 363 |
| Mean | 1786 | 4977 | 11970 | 2.544 | 84.17 | 33.5 | 41.01 | 1.995 | 20.551 | 48 | 363 |
| P.s.d. | 4.88 | 10.29 | 294 | .0622 | 0.134 | 0.29 | 0.203 | .0064 | .12123 | 0.8 | .29 |
| 22;11 | 1784 | 4976 | 11782 | 2.498 | 84.24 | 33.1 | 41.37 | 1.986 | 20.831 | 45 | 362 |
| 22;12 | 1785 | 4977 | 11244 | 2.385 | 84.24 | 33.0 | 41.32 | 1.987 | 20.794 | 45 | 362 |
| 22;13 | 1784 | 4979 | 11782 | 2.498 | 84.24 | 32.9 | 41.36 | 1.986 | 20.822 | 46 | 362 |
| 22;14 | 1781 | 4979 | 11223 | 2.385 | 84.10 | 33.3 | 41.35 | 1.988 | 20.805 | 45 | 362 |
| 22;15 | 1782 | 4978 | 11739 | 2.498 | 84.00 | 33.4 | 41.39 | 1.990 | 20.800 | 45 | 362 |
| Mean | 1783 | 4978 | 11550 | 2.453 | 84.17 | 33.2 | 41.36 | 1.987 | 20.811 | 46 | 362 |
| P.s.d. | 4.20 | 10.75 | 294 | .0622 | 0.123 | 0.21 | 0.155 | .0058 | .09861 | 0.5 | .12 |

Table 10. continued

| Time | RPM | power W | Q_w W | m_w kg/m | T_w C | T_a C | M_{air} kg/h | M_{gas} kg/h | A/F | O ₂ mv | T_e C |
|--------|------|------------|------------|---------------|------------|------------|-------------------|-------------------|--------|----------------------|------------|
| 22;30 | 1778 | 4971 | 11812 | 2.498 | 84.43 | 33.0 | 42.34 | 1.969 | 21.506 | 43 | 360 |
| 22;31 | 1780 | 4979 | 11816 | 2.498 | 84.50 | 33.1 | 42.24 | 1.971 | 21.433 | 43 | 359 |
| 22;32 | 1778 | 4979 | 11836 | 2.498 | 84.60 | 33.2 | 42.32 | 1.969 | 21.490 | 43 | 359 |
| 22;33 | 1779 | 4976 | 11288 | 2.385 | 84.55 | 32.9 | 42.34 | 1.968 | 21.515 | 43 | 359 |
| 22;34 | 1780 | 4970 | 11267 | 2.385 | 84.43 | 33.1 | 42.25 | 1.968 | 21.468 | 43 | 359 |
| Mean | 1779 | 4975 | 11600 | 2.453 | 84.50 | 33.1 | 42.30 | 1.969 | 21.483 | 43 | 359 |
| P.s.d. | 3.88 | 11.17 | 295 | .0622 | 0.092 | 0.18 | 0.135 | .0045 | .08456 | 0.1 | .46 |

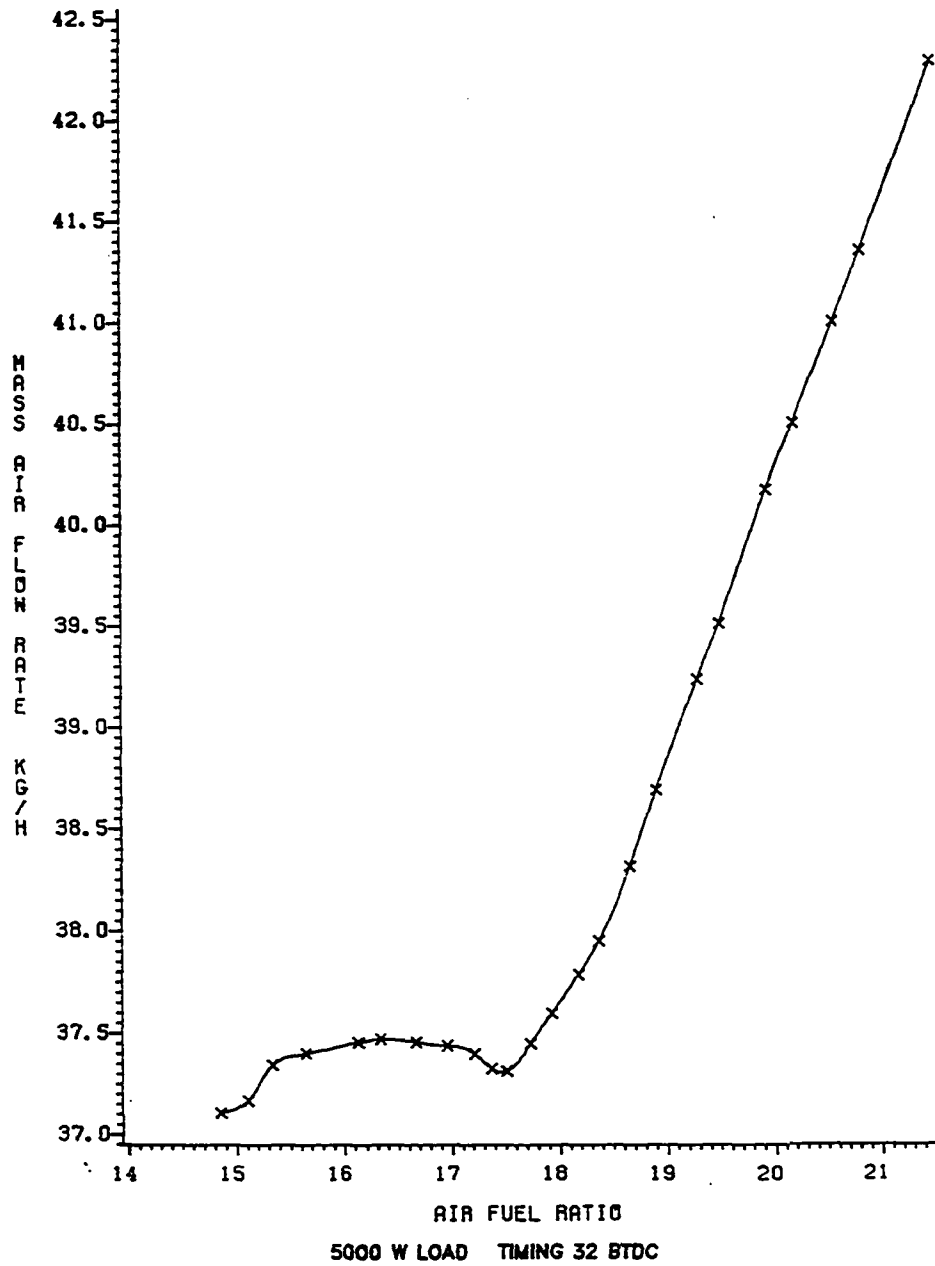


Figure 8. Mass gas flow rate vs. air fuel ratio

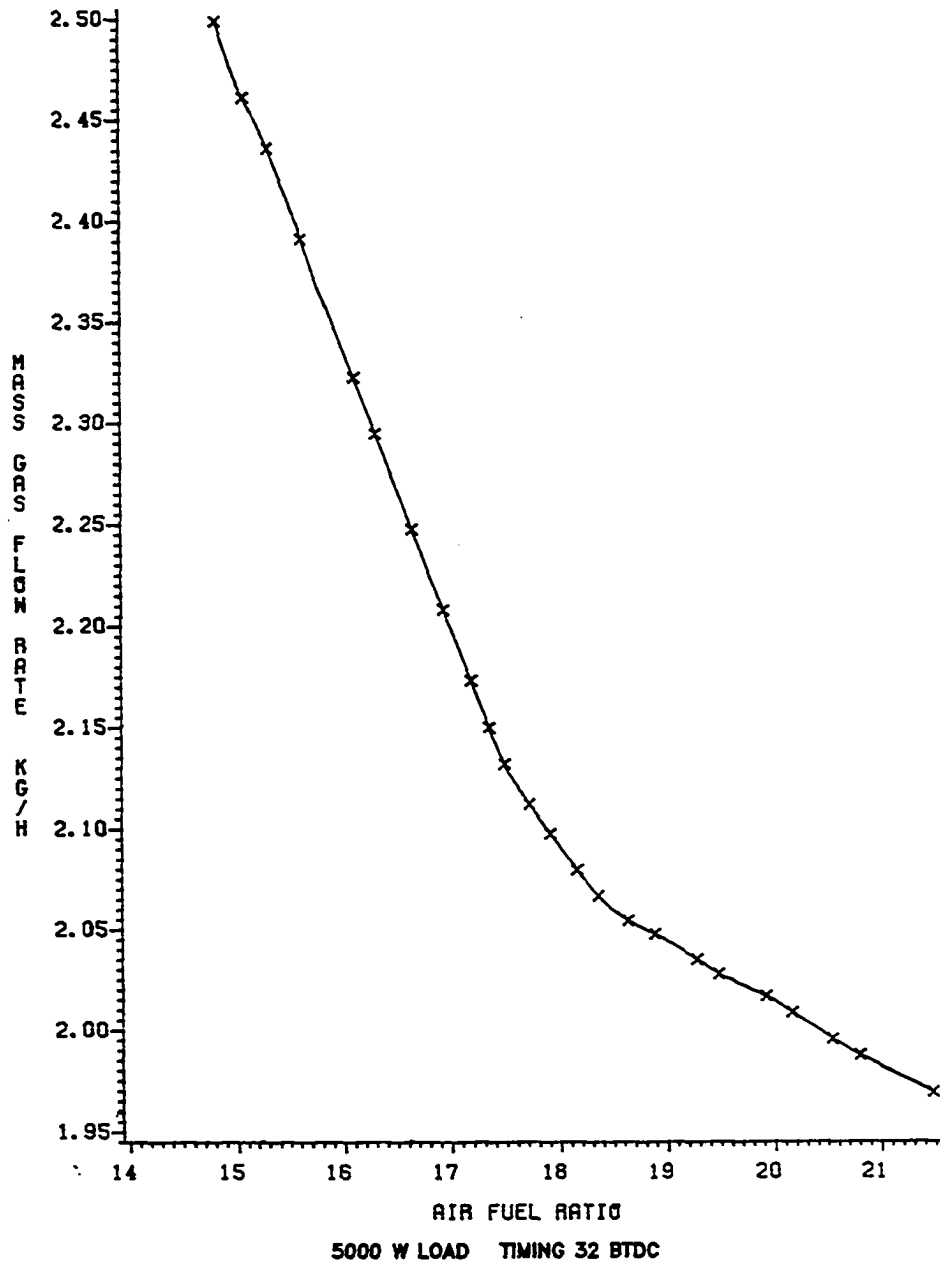
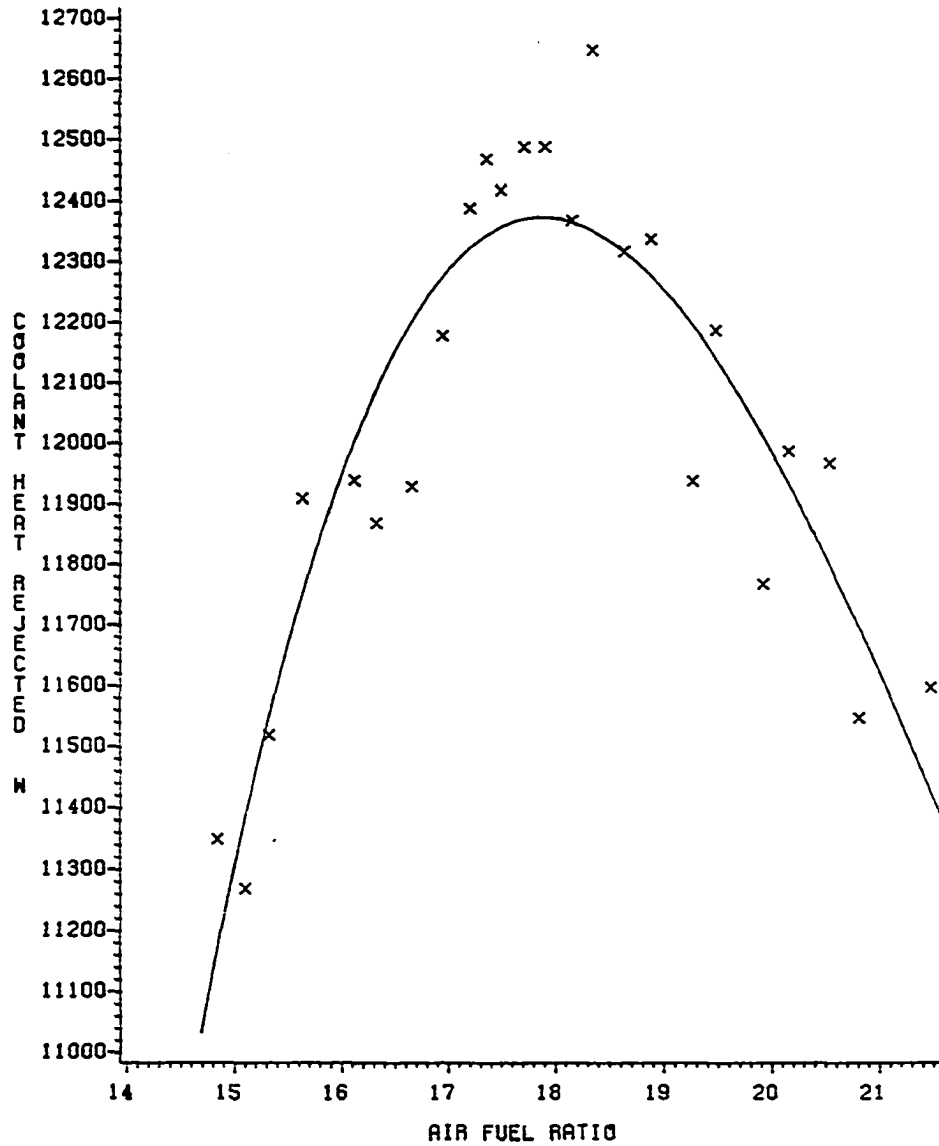


Figure 9. Mass air flow rate vs. air fuel ratio



5000 W LOAD TIMING 32 BTDC

Figure 10. Coolant heat rejected vs. air fuel ratio

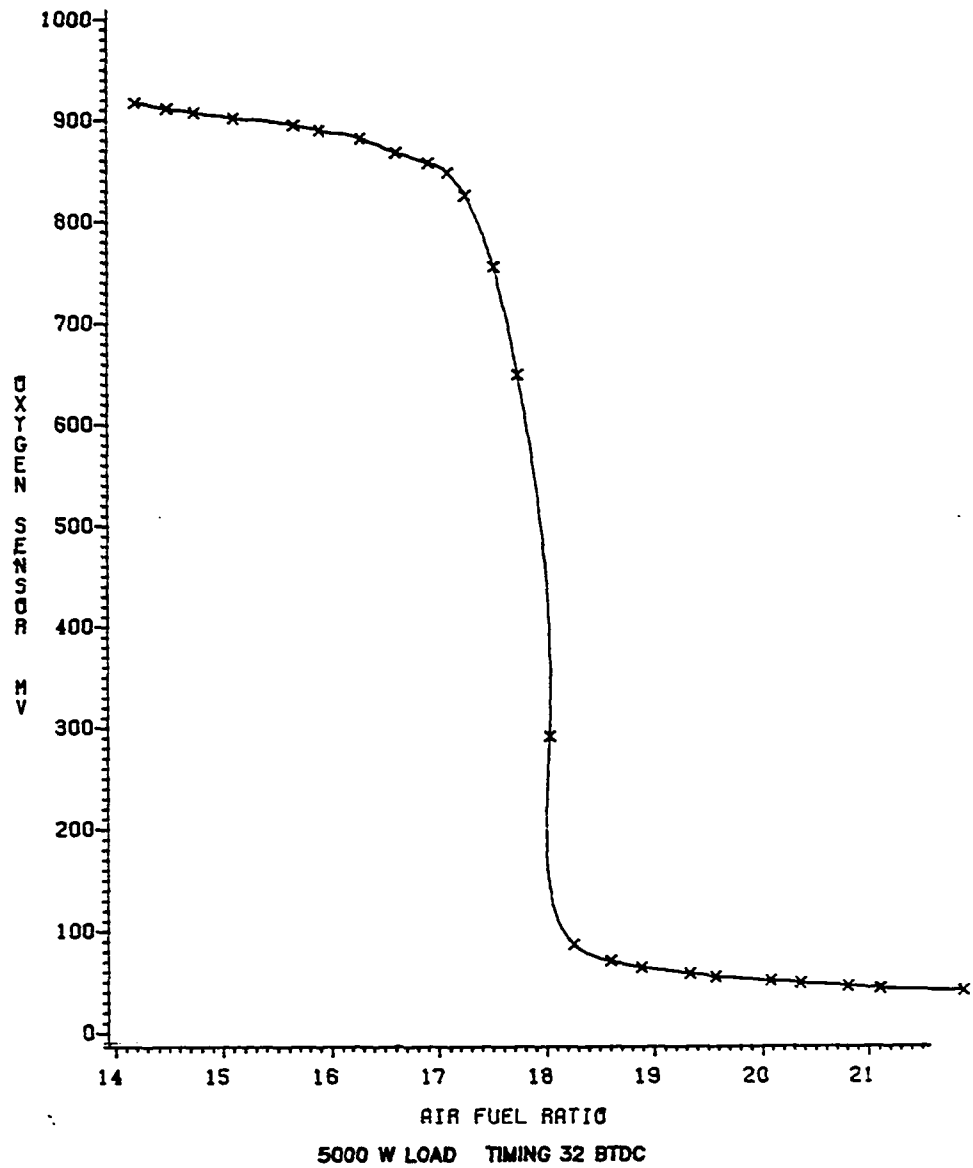


Figure 11. Oxygen sensor vs. air fuel ratio

CONCLUSIONS

1. An instrumentation and data logging system has been developed to measure: air temperature, gas temperature, coolant inlet and exit temperature, pressure drop across air and gas meter, exhaust gas temperature, coolant flow rate, electrical power output, and engine speed.

2. Commercially available sensors are used for all the above measurements.

3. A data collection period of 1 minute is used for data collection and this proved satisfactory for the data collected.

4. Less than 0.5% coefficient of variation in most of the results indicate reliable and repeatable results, but this does not give an indication of total error.

5. The use of a microcomputer in the data logging system permitted the measured variables to be computed into the following engine parameters: mass gas and air flow rate, air fuel ratio, electrical power output, coolant heat rejected, engine speed, exhaust gas temperature and oxygen sensor voltage.

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APPENDIX ASSEMBLED LISTING OF THE ASSEMBLY
LANGUAGE ROUTINE

| | | | | | |
|-------|----|-------|-----|--------|----------------------------|
| | 1 | | ORG | \$8A00 | Start of routine |
| | 2 | FLAG | EQU | \$8BF0 | Power meter flag |
| | 3 | FLAG1 | EQU | \$8BF1 | Water meter flag |
| | 4 | FLAG2 | EQU | \$8BF2 | 1 minute flag |
| | 5 | FLAG3 | EQU | \$8BF3 | Temporary time flag |
| | 6 | FLAG4 | EQU | \$8BF4 | Temporary time flag |
| | 7 | POW | EQU | \$8C00 | LSB power meter |
| | 8 | POW1 | EQU | \$8C01 | MSB power meter |
| | 9 | IN | EQU | \$C581 | VIA #2 IRA |
| | 10 | OUT | EQU | \$C580 | VIA #2 ORB |
| | 11 | KSWH | EQU | \$39 | Apple keyboard switch |
| | 12 | CLOCK | EQU | \$C400 | Clock card routine |
| | 13 | CDATA | EQU | \$0285 | Clock data |
| | 14 | SAVE | EQU | \$8C10 | Start of MicroMac data |
| | 15 | READ | EQU | \$8D00 | Start of MicroMac commands |
| | 16 | S1 | EQU | \$C0F4 | Serial status register |
| | 17 | S2 | EQU | \$C0F5 | Serial transmit data |
| | 18 | SCL | EQU | \$18 | Zero page screen data |
| | 19 | SCM | EQU | \$19 | Zero page screen data |
| 8A00: | A0 | 00 | 20 | LDY | #00 |
| 8A02: | 8C | 41 8B | 21 | STY | PT |
| 8A05: | 8C | F0 8B | 22 | STY | FLAG |
| 8A08: | 8C | F1 8B | 23 | STY | FLAG1 |
| 8A0B: | 8C | F2 8B | 24 | STY | FLAG2 |
| 8A0E: | A2 | 01 | 25 | LDX | #01 |
| 8A10: | A0 | 06 | 26 | LDY | #06 |
| 8A12: | 8C | 80 C5 | 27 | STY | OUT |
| 8A15: | AD | 81 C5 | 28 | LDA | IN |
| 8A18: | 8D | 00 8C | 29 | STA | POW |
| 8A1B: | C8 | | 30 | INY | |
| 8A1C: | 8C | 80 C5 | 31 | STY | OUT |
| 8A1F: | AD | 81 C5 | 32 | LDA | IN |
| 8A22: | 8D | 01 8C | 33 | STA | POW1 |
| 8A25: | A0 | 0A | 34 | LDY | #10 |
| 8A27: | 8C | 80 C5 | 35 | STY | OUT |

Zero flags

Save LSB from power meter

Save MSB from power meter

| | | | | | | |
|-------|----------|----|-------|-----|---------|-----------------------------------|
| 8A2A: | A0 00 | 36 | | LDY | #00 | |
| 8A2C: | AD F4 C0 | 37 | START | LDA | S1 | Check for empty output register |
| 8A2F: | 4A | 38 | | LSR | | |
| 8A30: | 4A | 39 | | LSR | | |
| 8A31: | 90 F9 | 40 | | BCC | START | |
| 8A33: | C8 | 41 | | INY | | |
| 8A34: | B9 00 8D | 42 | | LDA | READ,Y | Get command character |
| 8A37: | 8D F5 C0 | 43 | | STA | S2 | Send character |
| 8A3A: | CC 00 8D | 44 | | CPY | READ | Check for last character |
| 8A3D: | D0 ED | 45 | | BNE | START | |
| 8A3F: | A0 00 | 46 | | LDY | #00 | |
| 8A41: | 20 71 8B | 47 | GET | JSR | INPUT | Check for character |
| 8A44: | AD F5 C0 | 48 | | LDA | S2 | |
| 8A47: | C0 02 | 49 | | CPY | #02 | |
| 8A49: | F0 05 | 50 | | BEQ | GET3 | |
| 8A4B: | C9 3A | 51 | | CMP | #58 | See if the character is ":" |
| 8A4D: | D0 F2 | 52 | | BNE | GET | |
| 8A4F: | C8 | 53 | | INY | | |
| 8A50: | 20 71 8B | 54 | GET3 | JSR | INPUT | Check for character |
| 8A53: | AD F5 C0 | 55 | | LDA | S2 | |
| 8A56: | C8 | 56 | | INY | | |
| 8A57: | C9 3A | 57 | | CMP | #58 | See if the character is ":" |
| 8A59: | F0 1A | 58 | | BEQ | END | signifying the end of wanted data |
| 8A5B: | C0 03 | 59 | | CPY | #03 | |
| 8A5D: | D0 F1 | 60 | | BNE | GET3 | |
| 8A5F: | 20 5C 8B | 61 | | JSR | SC2 | Prepare for screen printing |
| 8A62: | 20 71 8B | 62 | GET2 | JSR | INPUT | Check for character |
| 8A65: | AD F5 C0 | 63 | | LDA | S2 | |
| 8A68: | 9D 10 8C | 64 | | STA | SAVE,X | Save wanted character |
| 8A6B: | 91 18 | 65 | | STA | (SCL),Y | Print character on screen |
| 8A6D: | E8 | 66 | | INX | | |
| 8A6E: | C8 | 67 | | INY | | |
| 8A6F: | C0 05 | 68 | | CPY | #05 | Check last of channel data |
| 8A71: | D0 EF | 69 | | BNE | GET2 | |
| 8A73: | A0 00 | 70 | | LDY | #00 | |

| | | | | | | | | |
|-------|----|----|----|-----|-----|-----|---------|-----------------------------|
| 8A75: | EC | 10 | 8C | 71 | END | CPX | SAVE | Check to see if any |
| 8A78: | D0 | C7 | | 72 | | BNE | GET | more channels to be read |
| 8A7A: | A0 | 08 | | 73 | | LDY | #08 | RPM routine |
| 8A7C: | 8C | 80 | C5 | 74 | | STY | OUT | |
| 8A7F: | AD | 81 | C5 | 75 | | LDA | IN | |
| 8A82: | 9D | 10 | 8C | 76 | | STA | SAVE,X | Save LSB |
| 8A85: | E8 | | | 77 | | INX | | |
| 8A86: | C8 | | | 78 | | INY | | |
| 8A87: | 8C | 80 | C5 | 79 | | STY | OUT | |
| 8A8A: | AD | 81 | C5 | 80 | | LDA | IN | |
| 8A8D: | 9D | 10 | 8C | 81 | | STA | SAVE,X | Save MSB |
| 8A90: | E8 | | | 82 | | INX | | |
| 8A91: | A0 | 7A | | 83 | | LDY | #122 | Clear RPM counter |
| 8A93: | 8C | 80 | C5 | 84 | | STY | OUT | |
| 8A96: | A0 | 0A | | 85 | | LDY | #10 | |
| 8A98: | 8C | 80 | C5 | 86 | | STY | OUT | |
| 8A9B: | A5 | 39 | | 87 | | LDA | KSWH | Temporarily store keyboard |
| 8A9D: | 48 | | | 88 | | PHA | switch | |
| 8A9E: | A9 | C4 | | 89 | | LDA | #\$C4 | Load clock card pointer |
| 8AA0: | 85 | 39 | | 90 | | STA | KSWH | in keyboard switch |
| 8AA2: | 20 | 00 | C4 | 91 | | JSR | CLOCK | Clock routine |
| 8AA5: | 68 | | | 92 | | PLA | | |
| 8AA6: | 85 | 39 | | 93 | | STA | KSWH | Restore keyboard switch |
| 8AA8: | A0 | 18 | | 94 | | LDY | #24 | |
| 8AAA: | 8C | 41 | 8B | 95 | | STY | PT | |
| 8AAD: | 20 | 5C | 8B | 96 | | JSR | SC2 | Prepare for screen printing |
| 8AB0: | 8A | | | 97 | | TXA | | |
| 8AB1: | 48 | | | 98 | | PHA | | |
| 8AB2: | A2 | 09 | | 99 | | LDX | #09 | |
| 8AB4: | BD | 85 | 02 | 100 | CL | LDA | CDATA,X | |
| 8AB7: | 91 | 18 | | 101 | | STA | (SCL),Y | Print time on the screen |
| 8AB9: | C8 | | | 102 | | INY | | |
| 8ABA: | CA | | | 103 | | DEX | | |
| 8ABB: | E0 | 00 | | 104 | | CPX | #00 | |
| 8ABD: | D0 | F5 | | 105 | | BNE | CL | |

| | | |
|-------|----------|-----|
| 8ABF: | 68 | 106 |
| 8AC0: | AA | 107 |
| 8AC1: | A0 06 | 108 |
| 8AC3: | 8C 80 C5 | 109 |
| 8AC6: | AD 81 C5 | 110 |
| 8AC9: | CD 00 8C | 111 |
| 8ACC: | D0 22 | 112 |
| 8ACE: | 9D 10 8C | 113 |
| 8AD1: | C8 | 114 |
| 8AD2: | 8C 80 C5 | 115 |
| 8AD5: | AD 81 C5 | 116 |
| 8AD8: | C9 00 | 117 |
| 8ADA: | F0 14 | 118 |
| 8ADC: | CD 01 8C | 119 |
| 8ADF: | D0 0F | 120 |
| 8AE1: | E8 | 121 |
| 8AE2: | 9D 10 8C | 122 |
| 8AE5: | E8 | 123 |
| 8AE6: | A0 01 | 124 |
| 8AE8: | 8C F0 8B | 125 |
| 8AEB: | A0 6A | 126 |
| 8AED: | 8C 80 C5 | 127 |
| 8AF0: | AD 87 02 | 128 |
| 8AF3: | CD F4 8B | 129 |
| 8AF6: | F0 25 | 130 |
| 8AF8: | 8D F4 8B | 131 |
| 8AFB: | A0 1A | 132 |
| 8AFD: | 8C 80 C5 | 133 |
| 8B00: | AD 81 C5 | 134 |
| 8B03: | 9D 10 8C | 135 |
| 8B06: | E8 | 136 |
| 8B07: | A0 2A | 137 |
| 8B09: | 8C 80 C5 | 138 |
| 8B0C: | AD 81 C5 | 139 |
| 8B0F: | 9D 10 8C | 140 |

CON

| | |
|-----|--------|
| PLA | |
| TAX | |
| LDY | #06 |
| STY | OUT |
| LDA | IN |
| CMP | POW |
| BNE | CON |
| STA | SAVE,X |
| INY | |
| STY | OUT |
| LDA | IN |
| CMP | #00 |
| BEQ | CON |
| CMP | POW1 |
| BNE | CON |
| INX | |
| STA | SAVE,X |
| INX | |
| LDY | #01 |
| STY | FLAG |
| LDY | #106 |
| STY | OUT |
| LDA | \$287 |
| CMP | FLAG4 |
| BEQ | CON2 |
| STA | FLAG4 |
| LDY | #26 |
| STY | OUT |
| LDA | IN |
| STA | SAVE,X |
| INX | |
| LDY | #42 |
| STY | OUT |
| LDA | IN |
| STA | SAVE,X |

Power meter routine

Get LSB of power meter counter
Compare with previously saved
LSB to see if counting has stopped
Save LSB

Get MSB of power meter counter
Compare with zero
Continue if zero
Compare with previously saved
MSB to see if counting had stopped

Save MSB

Set power meter flag
Get 10 s digit of clock output
Clear counter

Check to see if 10 s has elapsed

Save new 10 s digit
Water meter routine

Get LSB of water meter counter
Save LSB

Get MSB of water meter counter
Save MSB

| | | | | | | | |
|-------|----|----|-----|------|-----|---|-----------------------------------|
| 8B12: | E8 | | 141 | | INX | | |
| 8B13: | A0 | 5A | 142 | | LDY | #90 | |
| 8B15: | 8C | 80 | C5 | | STY | OUT | Clear water meter counter |
| 8B18: | A0 | 01 | | | LDY | #01 | |
| 8B1A: | 8C | F1 | 8B | | STY | FLAG1 | Set water meter flag |
| 8B1D: | AD | 89 | 02 | CON2 | LDA | \$289 | Get 1 min digit of clock output |
| 8B20: | CD | F3 | 8B | | CMP | FLAG3 | Check to see if 1 min has elapsed |
| 8B23: | F0 | 16 | | | BEQ | END2 | |
| 8B25: | 8D | F3 | 8B | | STA | FLAG3 | Save 1 min digit |
| 8B28: | A0 | 01 | | | LDY | #01 | |
| 8B2A: | 8C | F2 | 8B | | STY | FLAG2 | Set 1 min flag |
| 8B2D: | A0 | 06 | | | LDY | #06 | |
| 8B2F: | B9 | 87 | 02 | CL2 | LDA | \$287,Y | Get 1 min and 1 hour digits |
| 8B32: | 9D | 10 | 8C | | STA | SAVE,X | Save digits |
| 8B35: | E8 | | | | INX | | |
| 8B36: | 88 | | | | DEY | | |
| 8B37: | C0 | 00 | | | CPY | #00 | |
| 8B39: | D0 | F4 | | | BNE | CL2 | |
| 8B3B: | A0 | 0A | | END2 | LDY | #10 | |
| 8B3D: | 8C | 80 | C5 | | STY | OUT | Return to BASIC |
| 8B40: | 60 | | | | RTS | | |
| 8B41: | 00 | | | PT | HEX | 00 | Screen data pointer |
| 8B42: | 11 | 04 | 91 | | | | |
| 8B45: | 04 | 11 | 05 | | | | |
| 8B48: | 91 | 05 | 11 | | | | |
| 8B4B: | 06 | 91 | 06 | | | | |
| 8B4E: | 11 | 07 | 91 | | | | |
| 8B51: | 07 | 39 | 04 | | | | |
| 8B54: | B9 | 04 | 39 | | | | |
| 8B57: | 05 | B9 | 05 | | HEX | 110491041105910511069106110791073904B9043905B9C | |
| 8B5A: | B0 | 04 | | | HEX | B004 | Screen data |
| 8B5C: | AC | 41 | 8B | SC2 | LDY | PT | Prepare screen output routine |
| 8B5F: | C8 | | | | INY | | |

| | | | | | | | |
|-------|----|----|----|-----|-----|-------|------------------------------|
| 8B60: | B9 | 41 | 8B | 167 | LDA | PT,Y | |
| 8B63: | 85 | 18 | | 168 | STA | SCL | Set zero page screen pointer |
| 8B65: | C8 | | | 169 | INY | | |
| 8B66: | B9 | 41 | 8B | 170 | LDA | PT,Y | |
| 8B69: | 85 | 19 | | 171 | STA | SCM | |
| 8B6B: | 8C | 41 | 8B | 172 | STY | PT | |
| 8B6E: | A0 | 00 | | 173 | LDY | #00 | |
| 8B70: | 60 | | | 174 | RTS | | |
| 8B71: | AD | F4 | C0 | 175 | LDA | S1 | Check for character |
| 8B74: | 4A | | | 176 | LSR | | |
| 8B75: | 90 | FA | | 177 | BCC | INPUT | in input register |
| 8B77: | 60 | | | 178 | RTS | | |

--End assembly--

376 bytes

Errors: 0

Symbol table - alphabetical order:

| | | | | | | | |
|-------|---------|-------|---------|-------|---------|-------|---------|
| CDATA | =\$0285 | CL | =\$8AB4 | CL2 | =\$8B2F | CLOCK | =\$C400 |
| CON | =\$8AF0 | CON2 | =\$8B1D | END | =\$8A75 | END2 | =\$8B3B |
| FLAG | =\$8BF0 | FLAG1 | =\$8BF1 | FLAG2 | =\$8BF2 | FLAG3 | =\$8BF3 |
| FLAG4 | =\$8BF4 | GET | =\$8A41 | GET2 | =\$8A62 | GET3 | =\$8A50 |
| IN | =\$C581 | INPUT | =\$8B71 | KSWH | =\$39 | OUT | =\$C580 |
| POW | =\$8C00 | POW1 | =\$8C01 | PT | =\$8B41 | READ | =\$8D00 |
| S1 | =\$C0F4 | S2 | =\$C0F5 | SAVE | =\$8C10 | SC2 | =\$8B5C |
| SCL | =\$18 | SCM | =\$19 | START | =\$8A2C | | |

SECTION II. CONTROL OF ENGINE IGNITION TIMING,
AIR FUEL RATIO AND COOLANT TEMPERATURE
FOR RESEARCH OF AN ENGINE GENERATOR SET

Timothy M. P. Wall, M.S.

R. J. Smith, Ph.D.

S. J. Marley, Ph.D.

From the Department of Agricultural Engineering,
Iowa State University, Ames, IA 50011

INTRODUCTION

Interest in energy integrated farm systems has prompted studies of cogeneration electrical systems using biogas to produce electricity and thermal energy (Walker et al. 1984). The need for producing hot water on the farm may be as great as the need for electricity during winter and spring (Siebenmorgen et al. 1983). This suggests the possibility of using an engine generator set to convert biogas to a maximum amount of hot water and electricity. By controlling the air fuel ratio and ignition timing advance, it may be possible to find an optimum engine operating condition to produce a maximum useful energy conversion.

Biogas is a by-product of the anaerobic digestion of organic material, such as livestock waste. On the average the composition of biogas is by volume: one part carbon dioxide and two parts methane with traces (less than 3%) of other gases (MWPS-19 1975). Anaerobic digesters require heat to operate, and recovering thermal energy from an engine generator set is important when justifying the overall energy efficiency of a biogas system.

The ability to control internal combustion engines with electronics and microcomputers has been advanced in recent

years by the automotive industry. Concerns of fuel economy and exhaust gas emission control have prompted studies of engine performance. Fuel injection, ignition timing, exhaust gas recirculation and air intake are four factors considered for electronic control (Ikeura et al. 1980). Electronic control is needed to satisfy stringent exhaust emission standards as well as to maintain low fuel consumption. Using engine speed, air flow rate, air fuel ratio, ignition timing and exhaust gas recirculation as the five major variables, a control system has to be developed to maintain an optimum combination of these variables. Optimum combinations for different conditions, including acceleration, deceleration, highway driving, high speed driving, cold starting and hot starting, have to be developed and programmed into a microcomputer control system. Clearly, when applying this technology to an engine generator set operating on biogas, many of the control factors and variables do not apply; but the same techniques of control development can be used.

Other criteria for engine control systems are accuracy, response, stability, interactions, and cost (Hoard and Berry 1981). This can be handled by adaptive control (Toyoda et al. 1980) where allowances are made for vehicle deterioration, vehicle-to-vehicle variability caused by

variations in sensor and actuator characteristics, and by changing conditions such as atmospheric temperature, pressure and humidity. By controlling the errors due to these variabilities with automatic compensation using closed loop and self-learning control, it is possible to produce vehicles that have the fuel economy predicted by optimum control theory developed by computer simulation and actual engine study (Toyoda et al. 1980).

To develop a control system for the cogeneration of electricity and thermal energy using an engine generator and biogas, it is first necessary to determine the engine parameters to be controlled and the control variables. To produce electricity at a constant frequency, a synchronous generator is operated at a constant speed. Beyond a control system that maintains this constant speed, the engine speed, acceleration and, deceleration are control variables that need not be considered. Exhaust gas recirculation is used to reduce the emissions of nitrogen oxides in the exhaust (Obert 1973). Currently, there are no regulations regarding the control of exhaust gas pollutants of stationary engines in rural communities. This does not mean that the control of pollution should be ignored, and there have been studies of the emissions from engines operating on natural gas (natural gas is mostly methane) (Karim and Ali 1975;

Flemming and Allsup 1971). Operating an engine on natural gas at an equivalence ratio (equivalence ratio = actual mass air fuel ratio divided by the stoichiometric mass air fuel ratio) of 1.1 produces low quantities of pollutants with high power output. Operating an engine at other equivalence ratios does not produce significant pollutants, which suggests that the recirculation of exhaust gases is unnecessary.

Fuel injection is the preferred method used on liquid fueled engines for control of the air fuel ratio (Bowler 1980). Biogas mixes readily with air and can be supplied to an engine through a carburetor type gas mixer without fuel injection. Air intake is used largely as a control variable for metering fuel injection; for engine generator control, air intake only becomes a variable for the calculation of air fuel ratios.

This leaves ignition timing and air fuel ratio as the two main variables for the control of a biogas engine generator. Since in this particular case, the thermal output from the engine is important, it is necessary to consider engine coolant temperature as a third variable. As with the development of automotive control systems, the first task is to develop the optimum combination of the three variables for maximum useful energy conversion.

For the purpose of research and control it is desirable to make ignition timing electronically controlled instead of being controlled by the conventional breaker contact system that can only be varied by manually adjusting a distributor or magneto. Again the automotive industry has made advances in this area of technology. Duration of spark in a conventional system varies with engine speed (Ford 1974); and the first electronic systems maintained a constant spark duration, which was later improved to a constant energy spark (d'Orsay et al. 1979) with larger spark plug gaps to produce better fuel economy. New systems using microcomputer control set the timing advance by the means of memory stored maps that update the timing in accordance with engine speed and load (Grimm et al. 1980; Hoard and Berry 1981; Toyoda et al. 1980). All microcomputer systems must be able to update the engine data within a few engine revolutions, which can be a restriction when operating at high speeds.

Control systems for air fuel ratios on modern cars are necessary largely for pollution control. Three way catalyst systems for emission control of engines require air fuel ratios to be maintained at around stoichiometrically correct ratios (Hamburg and Shulman 1980). Engine coolant temperatures are measured only to control engines during

cold start-up procedures. Assuming that engine generators are kept in enclosures, extreme cold starting conditions should not be a problem.

Research to optimize engine performance on biogas has been conducted. An engine generator operating on biogas was found to have optimum electrical power output at full load and an equivalence ratio of between 1.25 and 1.67 with an ignition timing advance of up to 45 degrees before top dead center (BTDC) (Stahl et al. 1982). The optimum ignition timing for an engine operating on methane fuel at an equivalence ratio of 1.0 is 29 degrees BTDC and increases to about 32 degrees BTDC with the addition of 40% carbon dioxide by volume (Karim et al. 1982).

A concern with automotive engine operation is engine knock. Increasing the compression ratio of gasoline engines from the normal value of about 8:1 increases the likelihood of knock, but makes engines more efficient. Knock sensors have been developed in the automotive industry and have become part of automotive engine control (Currie et al. 1979). A study of knock in engines operating on natural gas indicated that the tendency for engine knock is not very dependent on compression ratio (Karim and Ali 1975). Ignition limits for various intake mixtures were also studied, showing a lean equivalence ratio of 1.67 was

achievable before the engine would misfire. A knock-free region for the engine was found within the 1.2 to 1.67 equivalence ratio range for all ignition advances. The remaining knock-free region is bounded by a maximum ignition advance of 22 degrees BTDC. Knock in other regions is not indicated as being severe, and it has been found that an engine operating on simulated biogas had an optimum compression ratio of 15:1 and an ignition advance of 30 degrees BTDC (Neyeloff and Gunkel 1980). Knock is therefore not considered a problem in the design of engine generator set controls.

Objectives

1. Develop a method of electronically controlling air fuel ratio, ignition timing, and coolant temperature of an engine generator set.
2. Find the optimum combination of air fuel ratio and ignition timing for different generator power outputs and a constant coolant temperature to produce thermal and electrical energy.

EQUIPMENT

To study the relation between air fuel ratio, engine timing, and coolant temperature, the experiments are conducted in a laboratory with an engine generator set operating on natural gas. The engine generator is a Kohler standby generator set Model 7.5R62 (Kohler Co.,¹ Kohler, WI 53044) supplied to operate on natural gas. The engine is a four cycle, liquid cooled, four cylinder engine, Model L654 directly connected to a synchronous generator rated at 6 kW. The electrical load used for the experiments is a resistor bank with a maximum load of 5 kW divided into increments of about 0.9 kW. The measured power output of the generator is considered as the total electrical energy conversion of the gas, and no attempt has been made to calculate the generator or engine efficiency separately.

Power, engine RPM, air and gas mass flow rate, air fuel ratio, exhaust gas temperature, coolant inlet and exit

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Mention of commercial products does not imply endorsement of these products by Iowa State University.

temperatures, air temperature and coolant heat rejected are all measured by an instrumentation and data logging system (Wall 1985). The engine speed is controlled by a mechanical governor connected to the carburetor and set to maintain an engine speed of 1800 RPM.

Timing Control

The engine was supplied with a magneto for producing the engine ignition. Control of engine timing is normally accomplished by manually rotating the magneto and simultaneously checking the timing marks on the engine flywheel with a timing light. To carry out research, this method of timing control is unsatisfactory; and an electronic timing control had to be developed. The electronic timing is computer controlled; but once set, it is independent of the computer, allowing the computer to carry out other tasks. The system is also capable of changing the timing without stopping the engine and is accurate to within 0.2 degrees of engine crankshaft revolution.

First, it is necessary to determine when a spark is needed. Four cylinder engines fire a cylinder twice every engine revolution, with the spark being advanced from top dead center of the cylinder. An engine revolution sensor is

therefore required to send two signals per engine revolution to the timing control system. This is accomplished by attaching a disk, with two protrusions 180 degrees apart, to the front pulley of the engine. These edges pass through an opto interrupt that is connected to an optoisolator in the control system (see Figure 1). The optoisolator is used to protect the electronics from accidental high voltage and also helps to reduce electrical noise. The signal from the optoisolator is shaped into a transistor transistor logic (TTL) pulse by a LM555 timer (National Semiconductor 1980). The disk on the engine is positioned to coincide with the timing marks on the engine flywheel so that pulses are sent to the control system when the engine pistons are at top dead center.

Next, a method for developing a pulse at the required timing advance is needed. For the purpose of design, an 18 degree BTDC timing is chosen for the calculations. Since there are two pulses per engine revolution produced by the opto interrupt, and two pulses per revolution are needed for the ignition advance, it is possible to consider an 18 degree advance as being a 162 degrees after top dead center (ATDC) timing. This simplifies the electronics and, although the timing is essentially half a revolution behind, will make no difference to the engine timing when the engine

is operating at constant speed. Since the engine is operated at a constant speed it at first seemed possible to develop a constant time delay type of control because the time taken for the engine to rotate 162 degrees will always be the same. The problem with this is that there is no means of starting the engine when a varying time delay is needed, and even at a constant speed the actual engine speed can vary as much as 50 RPM, depending on the generator load. To overcome this, an adaptive system that determines the time delay based on the length of time the engine takes to complete the last one half revolution is required. This can be done by using two high speed electronic clocks that develop pulses of different periods.

At the detection of a pulse from the engine sensor, a counter starts to count pulses from the slower clock. This counter is stopped by the next pulse from the engine sensor, which simultaneously starts a counter counting pulses from the faster clock. When the faster clock counter reaches the value of the slower clock counter, a timing pulse, using comparators, can be developed. This timing pulse can then be delivered to the engine before the next pulse from the engine sensor is received, hence providing timing advance. The counters are cleared before the start of the next cycle. To provide the 162 degree delay, the slower clock runs at

$162/180 = 0.9$, the speed of the faster clock.

The timing control system is connected to a computer with an internal clock that operates at 1 MHz. This is used directly for the faster clock, and the slower clock can be controlled from 0 to 0.999 by using three synchronous decade rate multipliers, SN74167 (Texas Instruments 1976). Figure 1 shows the SN74167s connected to a 6522 versatile interface adapter (VIA) (Rockwell International 1978). The VIA is controlled by the host computer and, once the output registers have been set, the SN74167s will operate at a constant rate until changed by the host computer.

Continuous control by the host computer is therefore not required. This system allows the timing delay to be altered from 0 to 179.82 degrees ATDC, which corresponds to a control of 0.18 to 180 degrees BTDC in increments of 0.18 degrees.

The size of counters needed for this system has to be determined. When the engine is operating at 1800 RPM the time between two consecutive engine sensor pulses is given by

$$T = (60/1800)/2 = 0.1667 \text{ seconds.}$$

A counter counting pulses from a 1 MHz clock would record 16667 counts in that time. A 16 bit counter can count up to $2^{16} = 65536$ pulses, which is enough for the timing control

system while the engine is operating at 1800 RPM. The system, however, must also work for engine start-up. With a 16 bit counter the minimum RPM that can be accommodated by the timing control is

$$\text{RPM} = (60/0.65536)/2 = 45.$$

By using a 20 bit counter the maximum count is $2^{20} = 1048576$ which can operate at speeds down to

$$\text{RPM} = (60/10.48576)/2 = 5.72.$$

This is slower than starter operation. Figure 2 shows five SN74161 4 bit counters wired as synchronous look ahead counters (Texas Instruments 1976). The SN7485 are 4 bit magnitude comparators. Two of these circuits are required, one for each half of an engine revolution.

Since the engine requires two pulses per revolution, the pulses from the engine sensors have to be conditioned to control the sequencing of the counters. Figure 1 shows the complete control hardware. The conditioned signal from LM555 #1 timer is connected to a SN74109 dual positive edge triggered flip-flop. The Q and \overline{Q} outputs of the SN74109 will be at opposite states and invert twice per engine revolution. Each is connected to one half of a dual monostable multivibrator, SN74221, which is wired to be triggered by a positive edge pulse so that the outputs pulse once per revolution, but at alternate engine sensor pulses.

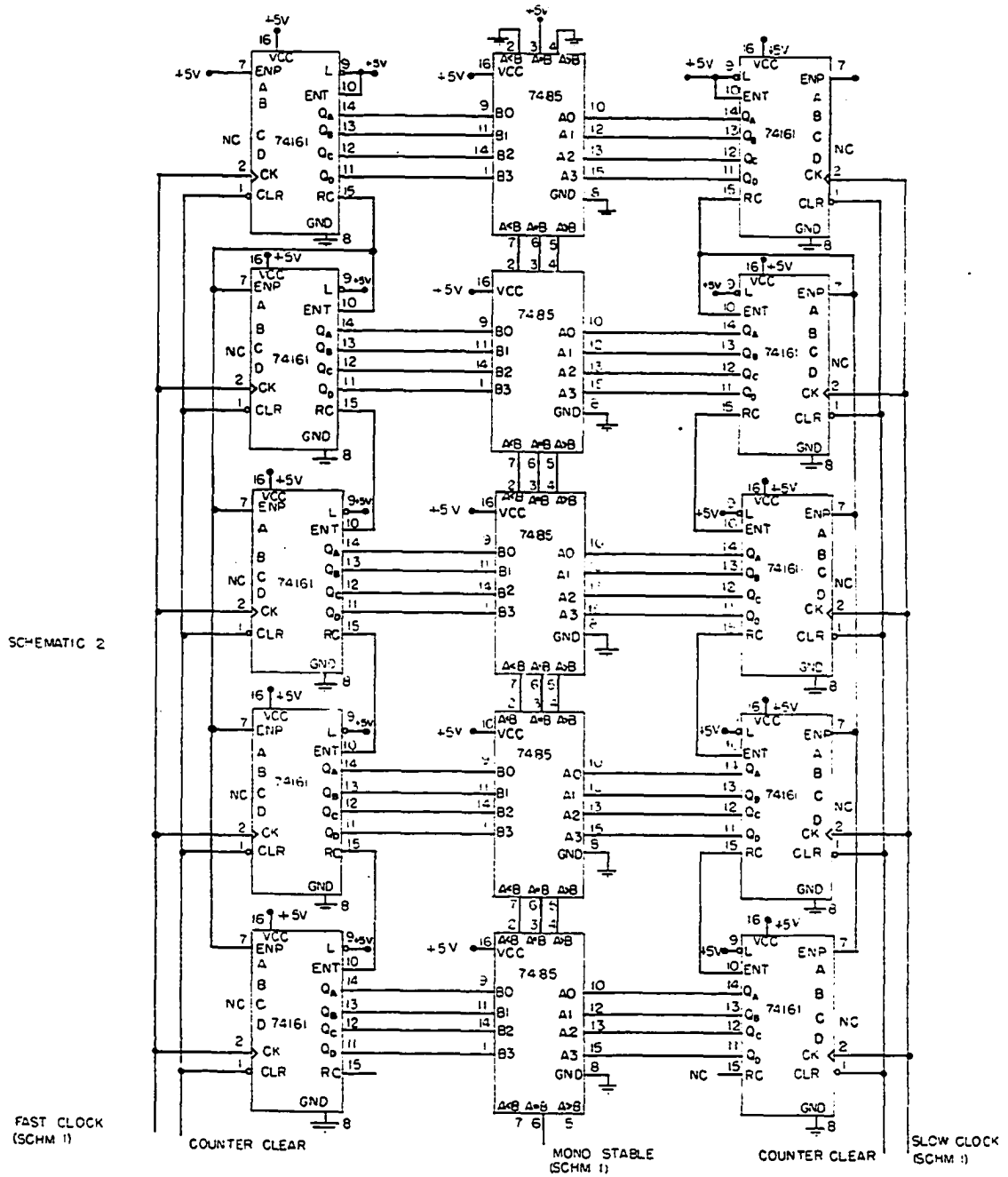


Figure 2. Timing counters

The SN74120 synchronous drivers start and stop the slow and fast clocks. The SN74120 #1 in Figure 1 controls the slow clock. Each half of SN74120 #1 controls one half of the engine revolution timing, and it is stopped and started by the outputs from the SN74221. The SN74120 #2 controls the faster clock and is started by the SN74221 signals, but is stopped by the return timing signal from the comparators. The SN74123, a dual retriggerable monostable multivibrator, conditions the return signal from the comparators to pulses of about 500 ns duration that are combined by the SN7406 hex inverters with open collector, high voltage outputs. The SN7406 outputs clear all counters, drive the SN74120 #2 and the LM555 #2 timer. The timer produces a pulse that drives the ignition coil via an optoisolator.

To use the pulse output to develop a spark, either a method of signaling the magneto is needed or the magneto must be replaced by an external ignition coil. General Motors Corporation has used a high energy electronic ignition system on some cars since 1975. The system consists of a magnetic pickup coil, electronic module, and high energy ignition coil. The magnetic pickup coil generates a small voltage pulse each time an engine spark is required. This voltage is amplified by the electronic module and controls a switching transistor also located in

the module. The switching transistor controls the primary current flow through the ignition coil. By replacing the magnetic pickup coil by the signal from the timing circuit, the electronic system is interfaced with the ignition coil.

The ignition coil itself is connected to the engine spark plugs via the magneto. An additional terminal post was added to the magneto cover so that the rotor distributed the ignition coil secondary current to the spark plugs in the correct firing order. The magneto coil is disconnected and all the high voltage connections are made with 8 mm high energy carbon cables. Electrical noise suppression capacitors are attached to the ignition coil.

In conventional ignition systems the term "dwell angle" refers to the number of degrees of rotation of the distributor cam during which the points are closed. This angle is one half the angle of rotation of the engine crankshaft in a four cylinder engine and is the period that the ignition coil primary winding is connected to the system's battery. The dwell angle varies with engine speed. In the electronic timing system the output of the LM555 #2 timer controls the period of time the ignition coil is disconnected. Initially, this was set to 2 ms which is a dwell of $90 - 90 \times 2 / 167 = 89$ degrees when the engine is operating at 1800 RPM. The system worked, but after 60

hours of operation the ignition coil burned out. The time period was then increased to 55 ms, giving a dwell angle of 60 degrees at 1800 RPM; consequently, no further problems were encountered. It must be noted that using a fixed time period causes the the amount of time the coil is disconnected to decrease with engine speed, and there will be a point when the engine will not run. At a constant speed of 1800 RPM this is not a problem.

Air Fuel Ratio

The gas carburetor mounted on the engine supplies gas to the engine through a needle valve. Adjustment to the gas flow rate can be made by turning the needle valve screw. The adjustment changes the air fuel ratio; thus by attaching a stepper motor to the screw, step changes in air fuel ratio can be made. The stepper motor rotates with 7.5 degree steps, and each step changes the equivalence ratio by about 0.006 for rich mixtures and by about 0.06 for lean mixtures. Since this method of control is restricting the gas flow, a constant air fuel ratio for different generator loads will require a change of stepper motor rotational position. The host computer operates the stepper motor.

Coolant Temperature

To maintain steady state conditions when collecting data, it is necessary to keep the engine coolant at a constant temperature. To do this, the cooling system radiator was removed and the coolant inlet was connected to a domestic cold water supply. The water flow rate is controlled by an electrically operated ball valve monitored by the host computer in the data logging system (Wall 1985).

EXPERIMENTAL PROCEDURE

Data were collected for the following conditions:

1.

Electrical load = 900 W (15% full load)

Coolant exit temperature = 85 ± 1 C

Range of ignition timing = 10.8 to 28.8 degrees BTDC

Range of air fuel ratio = 14.5 to 20.5

(equivalence ratio 0.84 to 1.19)

2.

Electrical load = 2600 W (43% full load)

Coolant exit temperature = 85 ± 1 C

Range of ignition timing = 10.8 to 32.2 degrees BTDC

Range of air fuel ratio = 14.5 to 21.3

(equivalence ratio 0.84 to 1.23)

3.

Electrical load = 5000 W (83% full load)

Coolant exit temperature = 85 ± 1 C

Range of ignition timing = 14.4 to 32.4 degrees BTDC

Range of air fuel ratio = 14.8 to 21.5

(equivalence ratio 0.86 to 1.25)

Full load is defined as the rated load for the engine generator set, which is 6000 W. The equivalence ratio is the air fuel ratio divided by the stoichiometric air fuel ratio of 17.26 for natural gas.

RESULTS AND DISCUSSION

All the results are shown graphically in Figures 3 through 11. The contour plots have timing and equivalence ratio as the x and y axis, respectively, with the z axis presented as percent of gas energy converted. This is derived in the following manner:

$$\text{Electrical power conversion} = \frac{E_p \times 3600 \times 100}{M_{\text{gas}} \times \Delta H_c} \quad (\%)$$

$$\text{Thermal energy conversion} = \frac{Q_w \times 3600 \times 100}{M_{\text{gas}} \times \Delta H_c} \quad (\%)$$

$$\text{Total energy conversion} = \text{Thermal} + \text{Electrical energy conversion}$$

where

E_p = electrical power W

M_{gas} = mass gas flow rate kg/h

ΔH_c = lower heat of combustion for methane

$$= 50.1 \times 10^6 \text{ J/kg.}$$

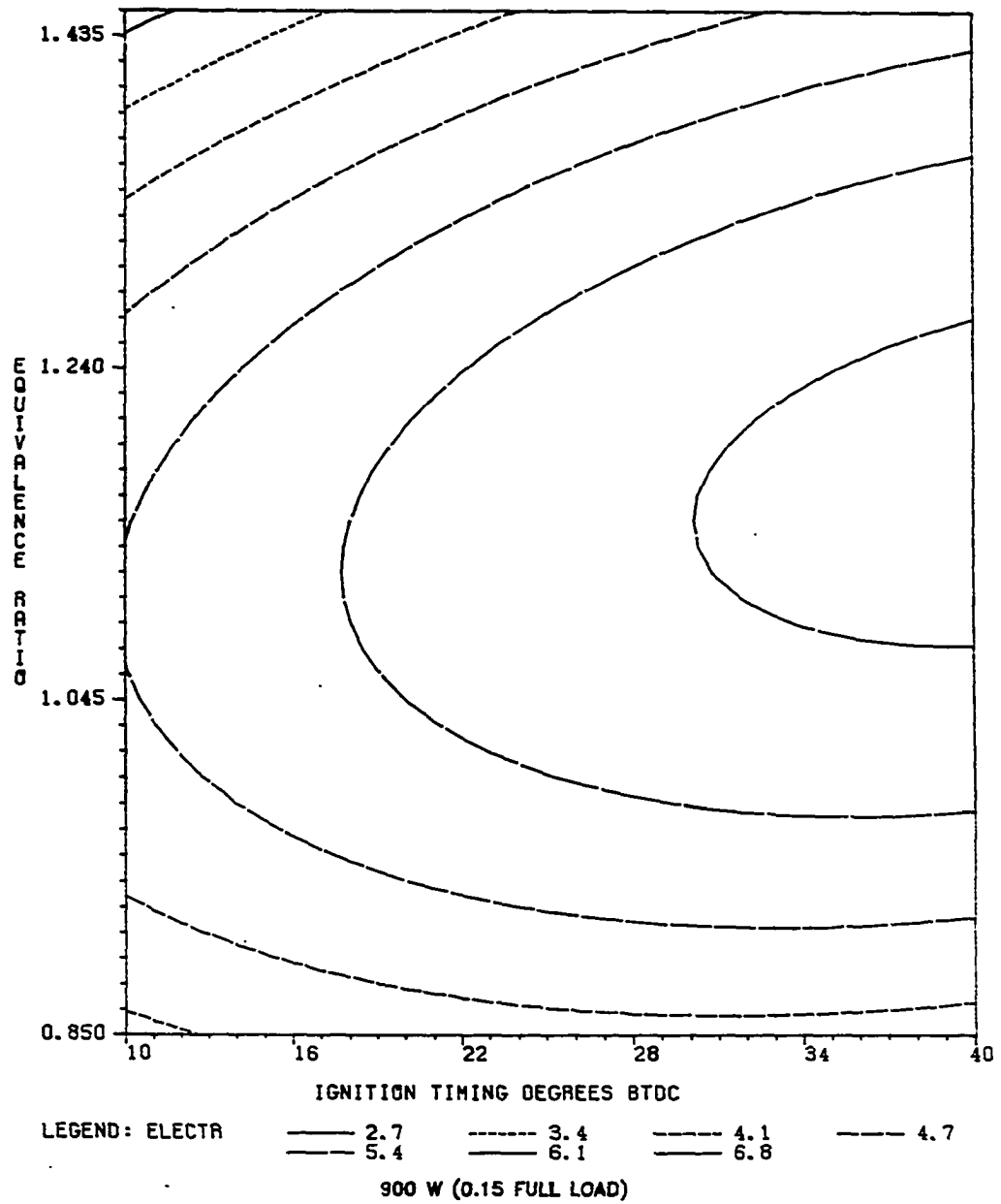


Figure 3. Electrical conversion vs. equivalence ratio and timing

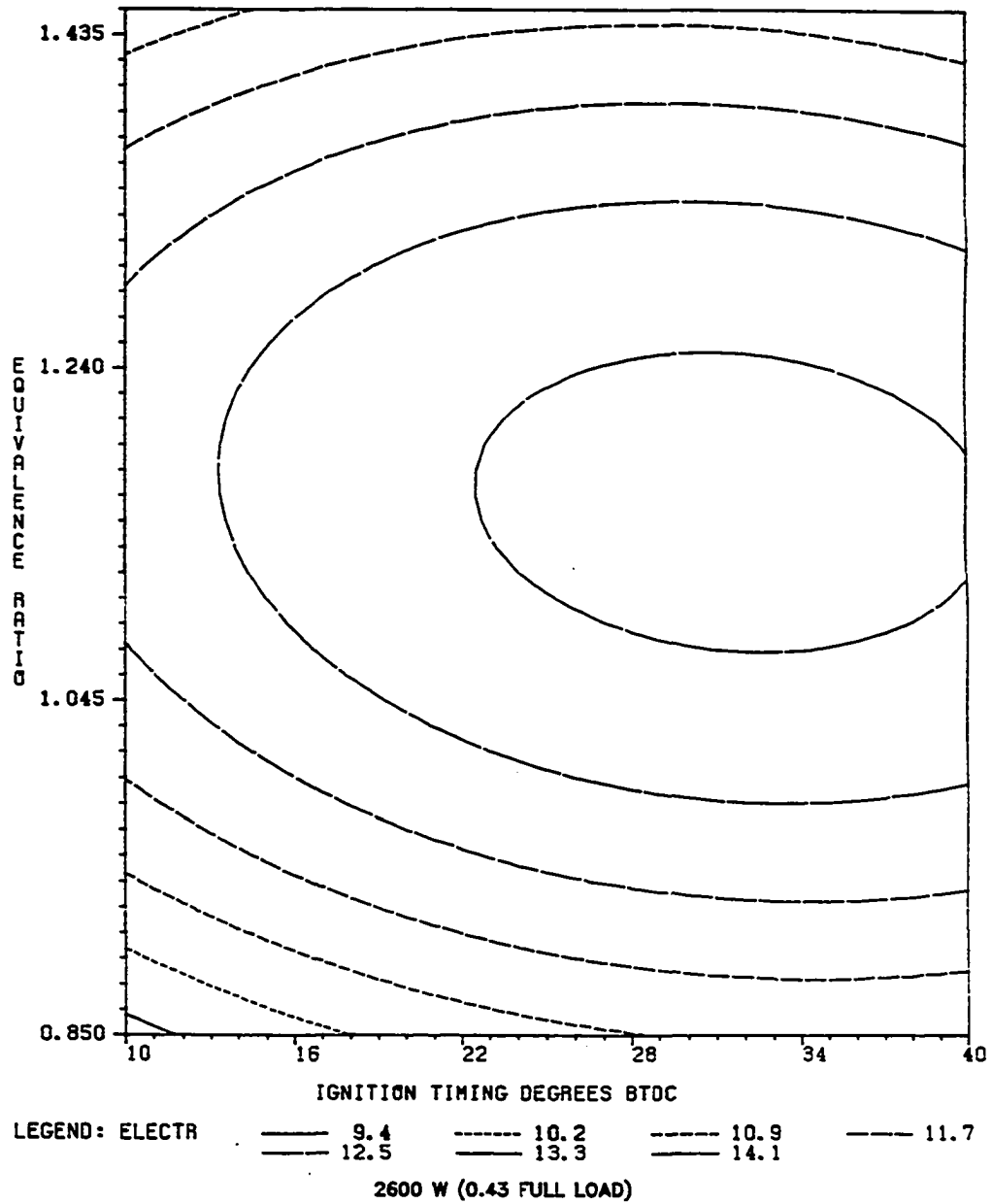


Figure 4. Electrical conversion vs. equivalence ratio and timing

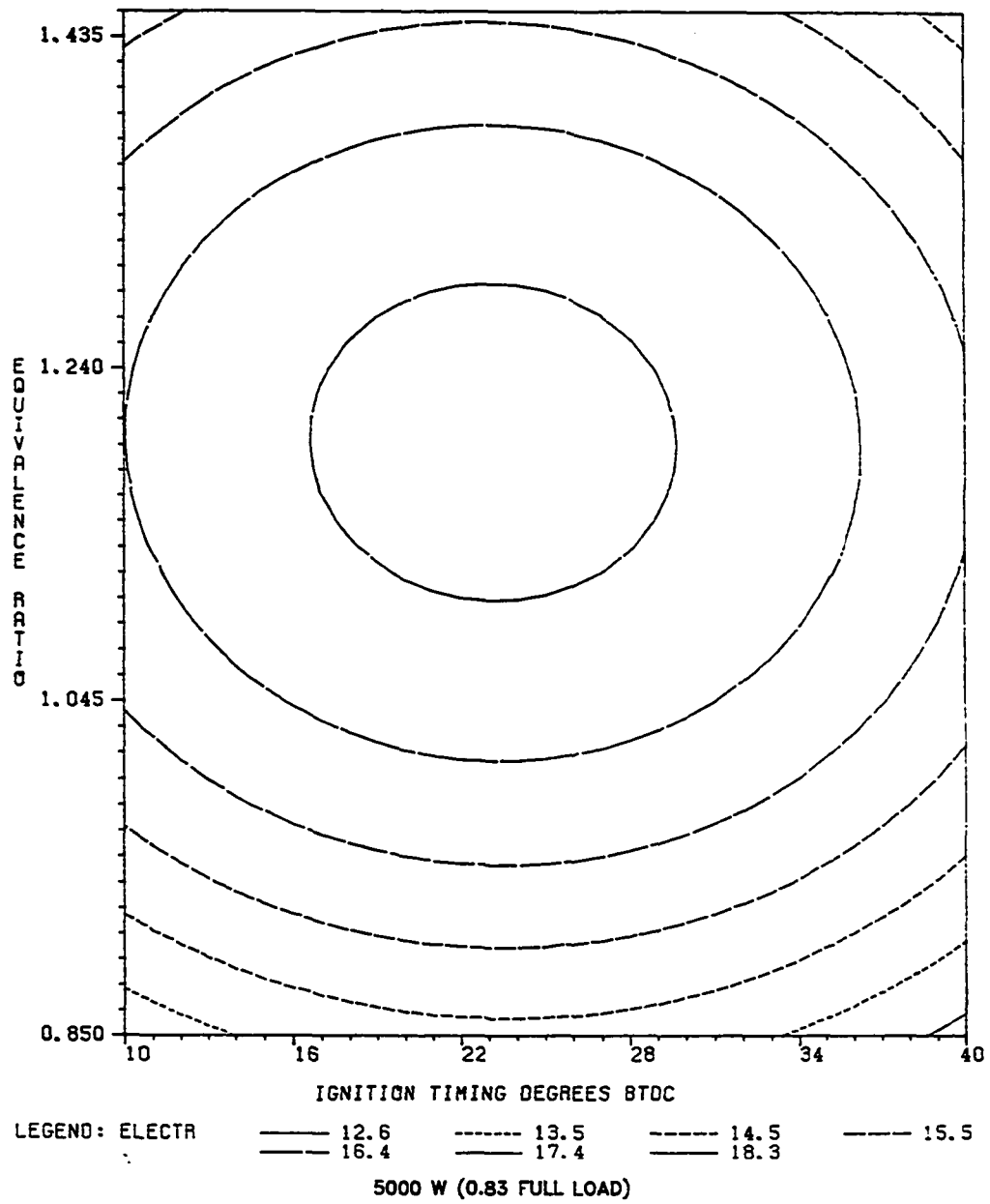


Figure 5. Electrical conversion vs. equivalence and timing

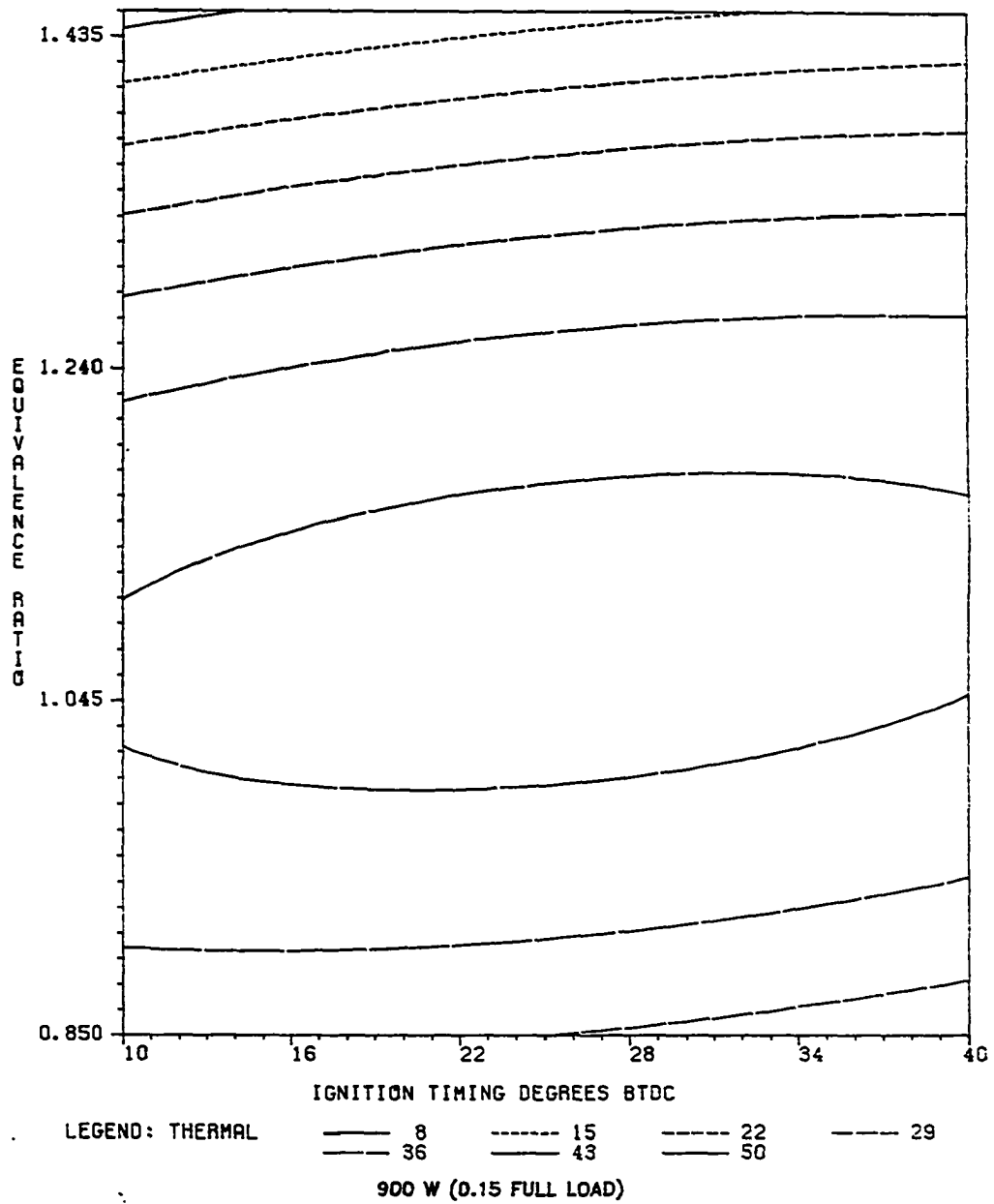


Figure 6. Thermal conversion vs. equivalence and timing

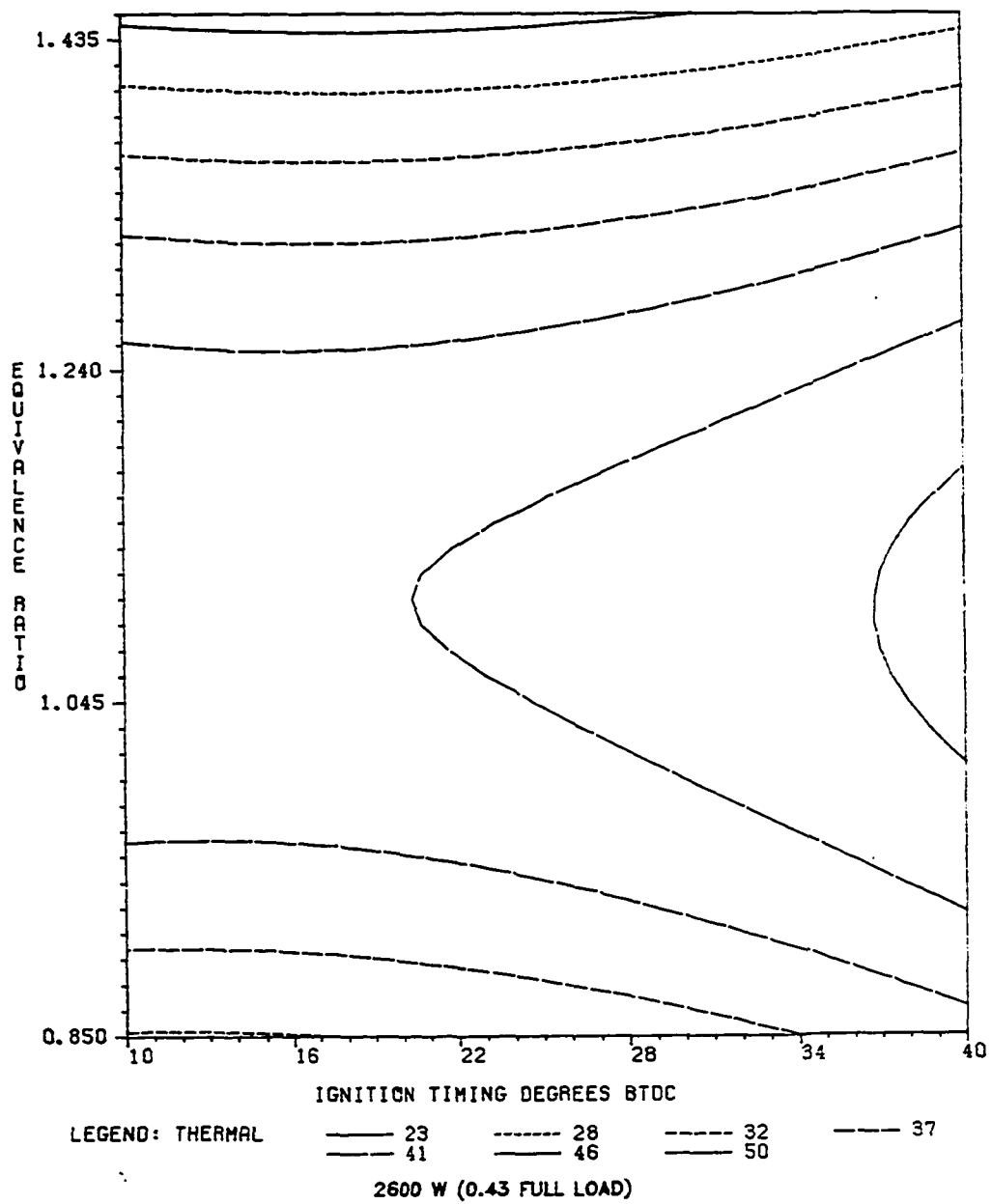


Figure 7. Thermal conversion vs. equivalence and timing

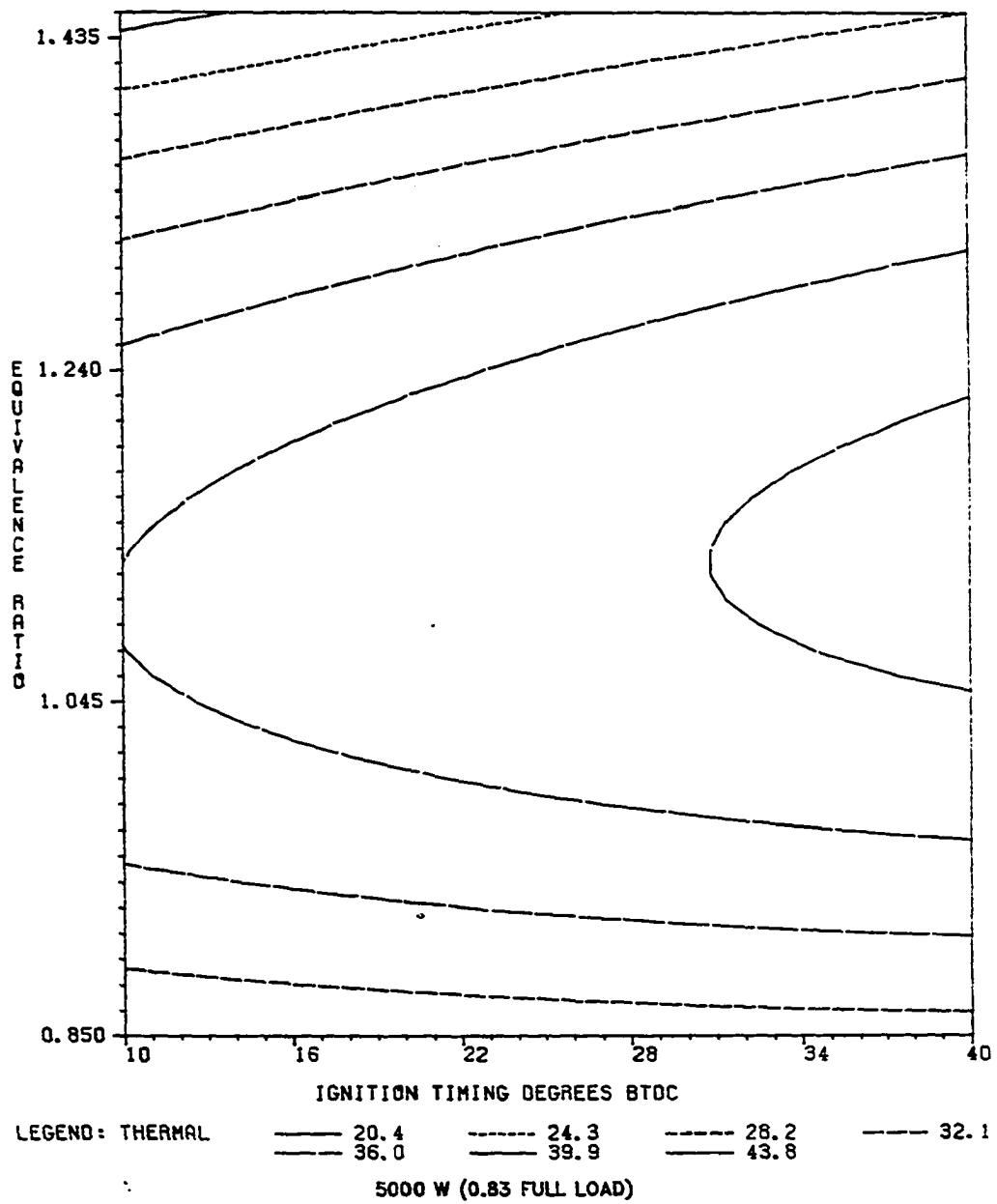


Figure 8. Thermal conversion vs. equivalence and timing

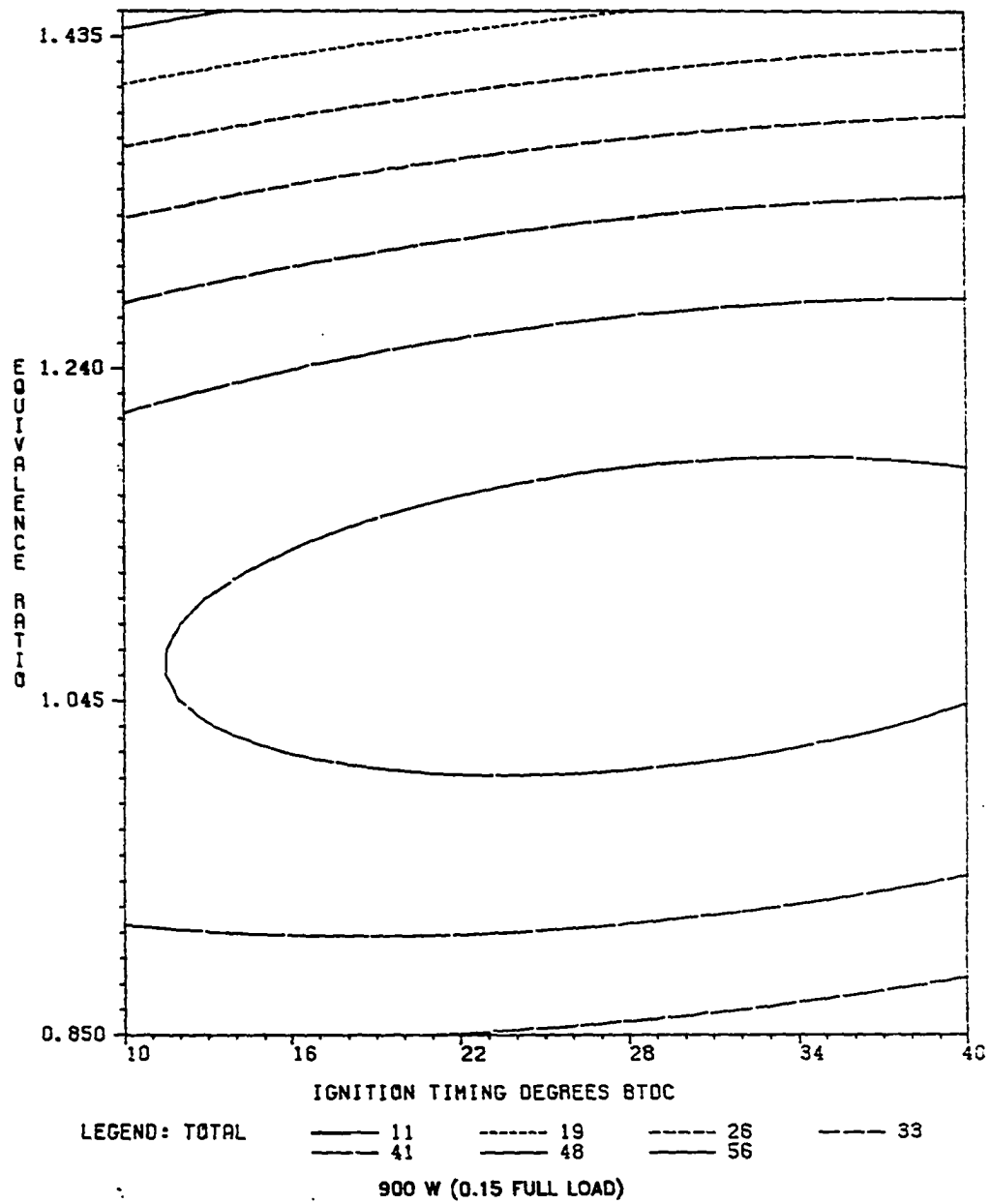


Figure 9. Total energy conversion vs. equivalence and timing

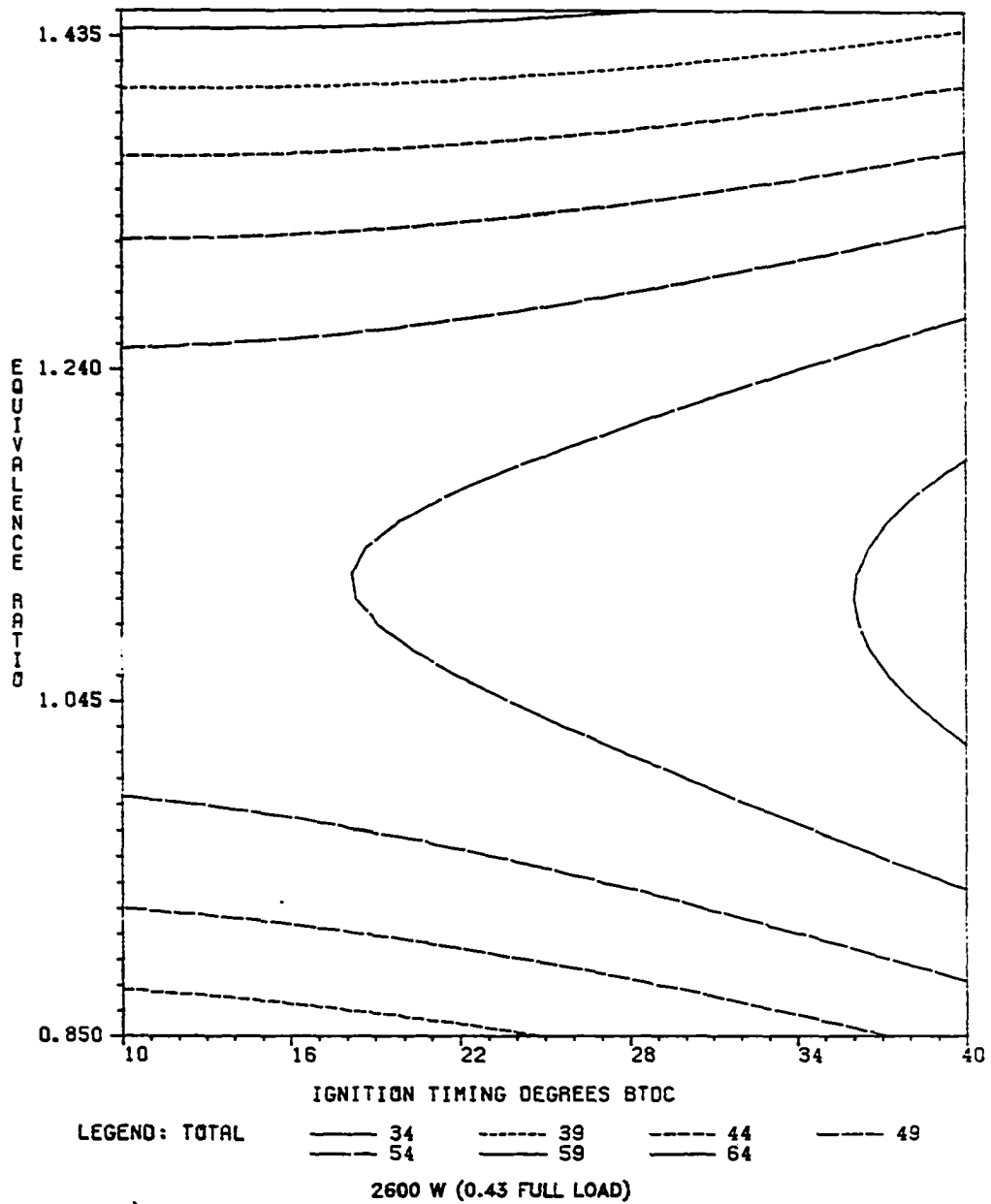


Figure 10. Total energy conversion vs. equivalence and timing

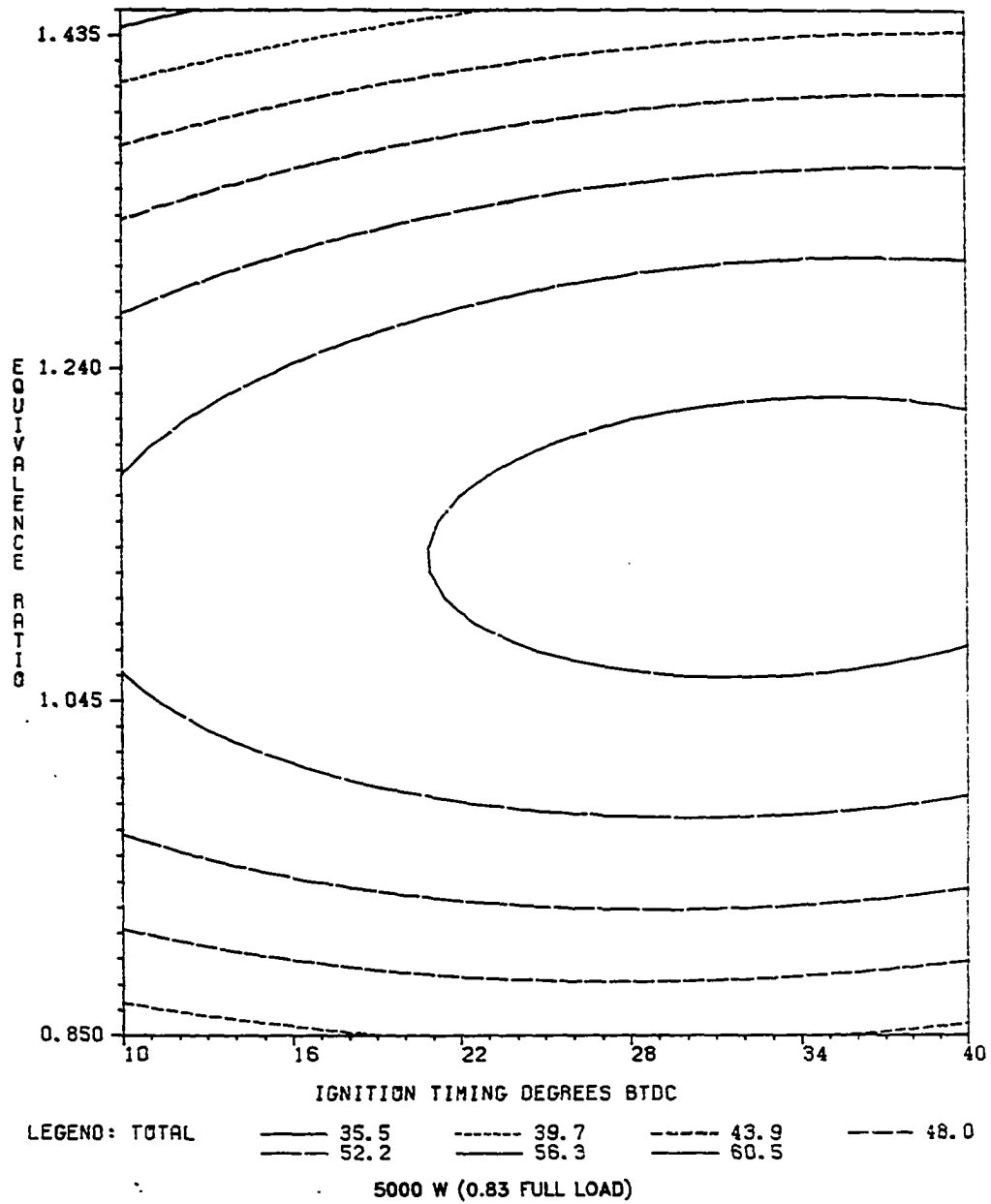


Figure 11. Total energy conversion vs. equivalence and timing

To obtain the contour plots a surface regression was applied to the data. The surface used had a 0.85 to 1.45 equivalence ratio and a 10 to 40 BTDC ignition timing advance range. This surface was chosen because the engine will operate within these limits.

The results of the regression for the electrical conversion are as follows:

900 W (15% full load)

optimum response

equivalence = 1.18

timing = 43.1

predicted conversion (%) at the optimum = 7.0

the solution is a maximum

response mean (%) = 5.6

R-square = 0.985

2600 W (43% full load)

optimum response

equivalence = 1.16

timing = 31.7

predicted conversion (%) at the optimum = 14.4

the solution is a maximum

response mean (%) = 12.7

R-square = 0.985

5000 W (83% full load)

optimum response

equivalence = 1.20

timing = 23.2

predicted conversion (%) at the optimum = 18.6

the solution is a maximum

response mean (%) = 16.9

R-square = 0.983.

R-square is the coefficient of variation and has a value in the range of 0 to 1, and can be used as a measure of regression acceptability. An R-square of near 1 indicates that the regression surface represents the data well.

Figures 3, 4 and 5 show the contour plots of the surfaces for electrical conversion. The contour plots indicate a reasonably flat surface near the optimum conditions. This permits the engine generator to operate well for a range of engine variables near the optimums. It appears that for all three loads an equivalence ratio within the range of 1.1 to 1.26 will produce close to optimum performance. The optimum timing is more dependent on load and the optimum range for timing becomes smaller for increasing loads (see Figure 5). The ignition timing also

needs to be less advanced for increasing load. The greater the power out of the generator, the more efficient the system is for all operating conditions.

The results of the regression model for thermal energy conversion are:

900 W (15% full load)

optimum response

equivalence = 1.09

timing = 26.2

predicted conversion (%) at the optimum = 51.8

the solution is a maximum

response mean (%) = 46.4

R-square = 0.959

2600 W (43% full load)

optimum response

equivalence = 1.11

timing = 14.4

predicted conversion (%) at the optimum = 45.3

the solution is a saddle point

response mean (%) = 42.4

R-square = 0.948

5000 W (83% full load)

optimum response

equivalence = 1.19

timing = 87.2

predicted conversion (%) at the optimum = 48.1

the solution is a maximum

response mean (%) = 39.1

R-square = 0.956.

Figures 6, 7 and 8 show the contour plots of the regression surfaces for the thermal energy conversion. The results and the figures show that the optimum conditions are not all within the operating range of the engine. The equivalence ratio has an optimum range of approximately 1.03 to 1.19, and the amount of thermal energy produced is not very dependent on engine timing. From the response means, the thermal energy conversion increases as the electrical load decreases.

Total energy conversion results are as follows:

900 W (15% full load)

optimum response

equivalence = 1.09

timing = 29.0

predicted conversion (%) at the optimum = 58.4

solution is a maximum

response mean (%) = 52.0

R-square = 0.964

2600 W (43% full load)

optimum response

equivalence = 1.12

timing = 5.9

predicted conversion (%) at the optimum = 58.1

solution is a saddle point

response mean (%) = 55.2

R-square = 0.963

5000 W (83% full load)

optimum response

equivalence = 1.14

timing = 33.4

predicted conversion (%) at the optimum = 61.9

solution is a maximum

response mean (%) = 55.9

R-square = 0.967

The regression surfaces for the total energy conversion are shown in Figures 9, 10 and 11. The optimum range of the

equivalence is about 1.03 to 1.15 for the operating range of the engine. It appears, again, that the timing has little effect on the optimum operation of the engine for total energy conversion. The response means and optimums indicate that the total energy conversion is roughly constant for all loads.

CONCLUSIONS

1. By using counters and comparators an electronic method of controlling the ignition timing to within 0.2 degrees has been developed. Air fuel ratio is controlled with a stepper motor and needle valve. The coolant temperature is controlled by an electric ball valve.

2. For electrical loads of 15%, 43% and 83% of full load and a constant coolant temperature of 85 C the following optimum conditions for equivalence ratio and ignition timing were found:

| energy | equivalence range | ignition timing |
|------------|-------------------|-------------------------|
| electrical | 1.12 to 1.28 | 23 BTDC (83% full load) |
| | 1.05 to 1.24 | 32 BTDC (43% full load) |
| | 1.07 to 1.27 | 43 BTDC (15% full load) |
| thermal | 1.03 to 1.19 | not strongly dependent |
| total | 1.03 to 1.15 | not strongly dependent. |

The percentage of gas converted to electrical energy was greatest near full load. The thermal energy conversion declined as the load increased; but the total energy conversion remained approximately unchanged.

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SECTION III. AIR FUEL RATIO CONTROL OF AN ENGINE
GENERATOR SET

Timothy M. P. Wall, M.S.

R. J. Smith, Ph.D.

S. J. Marley, Ph.D.

From the Department of Agricultural Engineering,
Iowa State University, Ames, IA 50011

INTRODUCTION

The topic of energy integrated farms has been thoroughly discussed (Walker et al. 1984), and an anaerobic digester producing biogas becomes a viable part of the system if the biogas can be utilized. Biogas, on the average, contains one part carbon dioxide and two parts methane with traces (less than 3%) of other gases (MWPS-19 1975). An engine generator operating on biogas produces thermal and electrical energy, both useful energies in a farm environment. In a preliminary investigation, a mathematical model simulating the thermal and electrical energy flows of an engine generator system operating on a swine farm indicated that the demand for thermal energy was greater than for electrical energy at certain times of the year (Siebenmorgen et al. 1983).

It has been found that by varying the ignition timing, air fuel ratio, and electrical load of an engine generator set, optimum operating conditions can be found for producing thermal and electrical energy from biogas (Wall 1985). Thermal and electrical energy are considered as the useful energy that can be recovered as hot water and electricity, respectively. Using natural gas (methane), the optimum

operating conditions for total (electrical + thermal) energy conversion were found when the equivalence ratio (equivalence ratio = actual mass air fuel ratio divided by the stoichiometric mass air fuel ratio) is in the range of 1.03 to 1.15. Total energy conversion was also shown not to be strongly dependent on ignition timing. The maximum electrical energy conversion at near full load occurs with an ignition timing of 23 degrees before top dead center (BTDC), and an equivalence ratio in the range of 1.1 to 1.26. The thermal energy reaches a peak when the equivalence ratio is in the range of 1.03 to 1.19, and is also, not strongly dependent on ignition timing. For biogas, the results are expected to be similar with the exception of the ignition timing which, should be advanced about another 3 degrees BTDC (Karim et al. 1982).

Keeping the equivalence ratio in the range of 1.03 to 1.15, an ignition timing of about 23 degrees BTDC, and near full load, is indicated to be the optimum way to use an engine generator to cogenerate electricity and thermal energy from biogas. The air fuel ratio of an engine generator using a gas mixing type carburetor will vary with changes in gas quality, atmospheric pressure, temperature and humidity. To optimize the energy conversion it is necessary to control the air fuel ratio for all operating

conditions, keeping the equivalence ratio within the range of 1.03 to 1.15.

The automotive industry has used air fuel ratio control in automobiles since the early 1970s. Three-way catalytic converters used to control the emissions in engine exhaust require engines to operate at, or near, stoichiometry; and there are many publications on closed-loop air fuel ratio control (Hamburg and Shulman 1980; Cederquist et al. 1979). Many of these control systems use ZrO_2 oxygen sensors in the exhaust gas to measure the oxygen content.

The zirconia type oxygen sensors consist of an yttria doped ZrO_2 ceramic with internal and external platinum electrodes exposed to the air and exhaust gas (Cook et al. 1983). When the electrodes experience a difference in the partial pressure of oxygen between the exhaust gas and air, the voltage generated is governed by the Nernst equation:

$$V = \frac{RT}{4F} \ln \left(\frac{P_{\text{O}_2\text{exh}}}{P_{\text{O}_2\text{atm}}} \right)$$

where

$P_{\text{O}_2\text{exh}}$ = partial pressure of oxygen in the exhaust gas

$P_{\text{O}_2\text{atm}}$ = partial pressure of oxygen in the atmosphere

R = gas constant

F = Faraday constant

T = absolute temperature.

This voltage abruptly changes at the point of stoichiometry, going from a voltage of about 900 mV for an equivalence ratio of 0.95 to 60 mV for an equivalence ratio of 1.05 when operating at a temperature of 550 C (Young and Bode 1979). The time response of these sensors to a change in air fuel ratio has been shown to be dependent on the speed of the engine and whether the change is from rich to lean or lean to rich but it is typically less than 200 ms (Cook et al. 1983).

The ZrO_2 sensor seems suited to the requirements of controlling an engine generator air fuel ratio. Since the response is dependent on the partial pressures of the oxygen in the exhaust gas and atmosphere the stoichiometric point can be found for any fuel. Initially, the only disadvantage noted is that the step response of the sensor is at an equivalence ratio of 1.0 instead of greater than 1.03. The temperature dependency of the sensor, however, causes the step response of an actual sensor to move away from the ideal indicated by the Nernst equation. A sensor operating at a temperature of 370 C shows a response near an equivalence ratio of 1.03 (Logothetis 1980). The temperature dependency of actual sensors also limits the sensors to functioning correctly only at temperatures above

325 C (Young and Bode 1979).

By using a ZrO_2 sensor, a control system has been designed to optimize the use of an engine generator set operating on natural gas. The experimental procedure is shown here.

Objectives

1. Validate the voltage output from a ZrO_2 oxygen sensor.
2. Develop a control circuit and controller to maintain the equivalence ratio in the range of 1.03 to 1.15 without the use of a microprocessor.

EQUIPMENT

Engine and Sensors

To evaluate the performance of automatic air fuel ratio control, an engine generator set operating on natural gas was installed in a laboratory. The engine generator is a Kohler standby generator set, Model 7.5R62 (Kohler Co.,¹ Kohler, WI 53044). The engine is four cycle, liquid cooled, four cylinder, engine model L654 directly connected to a synchronous generator rated at 6 kW. The electrical load used for the experiments is a resistor bank with a maximum load of 5 kW divided into steps of 0.9 kW.

Power, engine RPM, air and gas mass flow rate, air fuel ratio, exhaust gas temperature, coolant inlet and exit temperatures, coolant heat rejected and air temperature are all measured by an instrumentation and data logging system (Wall 1985). The engine RPM is controlled by a mechanical governor connected to the carburetor set to maintain an engine speed of 1800 RPM.

¹Mention of commercial products does not imply endorsement of these products by Iowa State University.

Oxygen sensor

The exhaust gas oxygen sensor used is part of the Ford Motor Company's electronic control system (Derato 1982). The sensor is made of ZrO_2 and placed in the exhaust pipe at a place where the temperature of the exhaust is about 350 C. This is approximately 200 mm from the manifold for the engine used in these experiments. The output from the sensor is connected directly to the instrumentation system with a load resistor of $2.2\text{ M}\Omega$ connected in parallel with the sensor.

Air fuel ratio

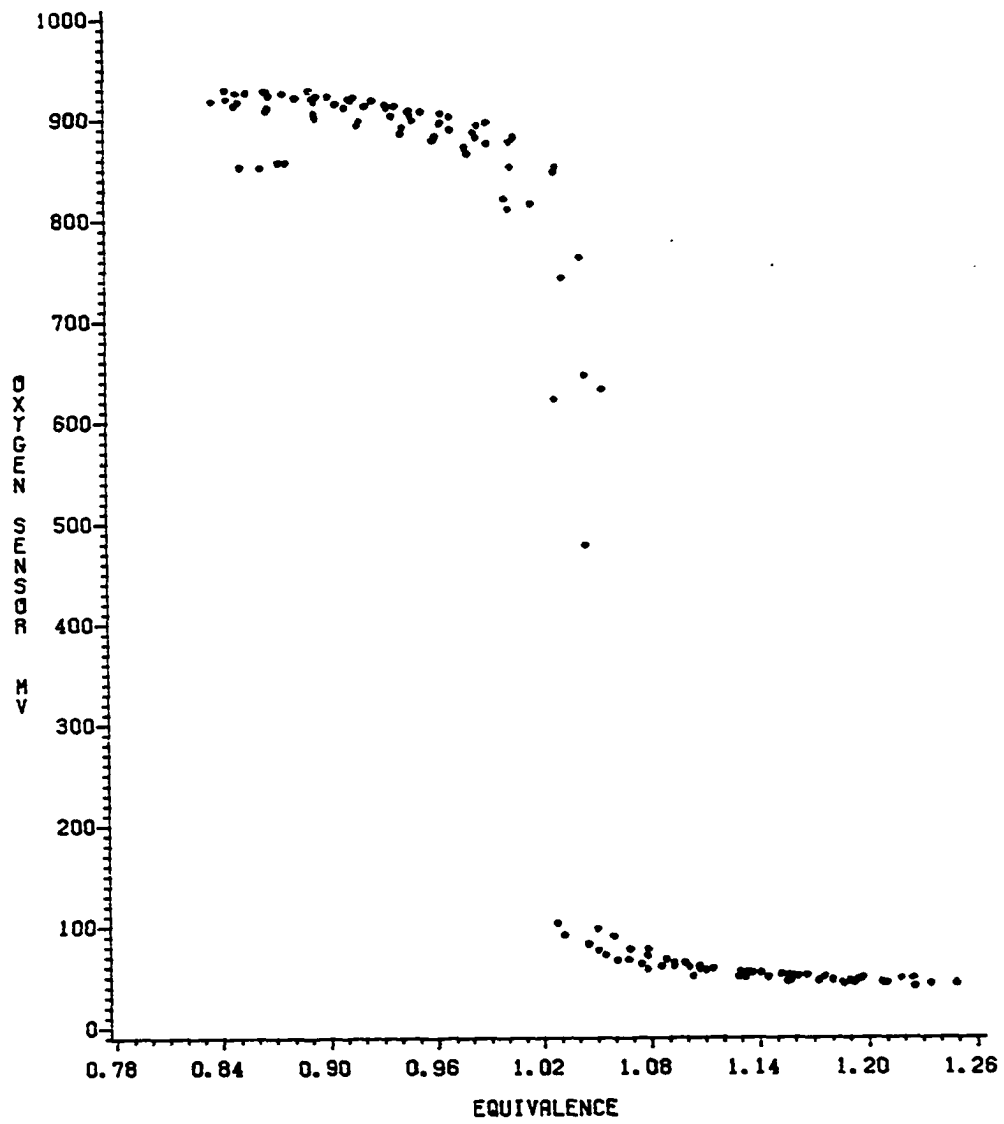
To build an electronic air fuel ratio control system the air fuel ratio of the engine has to be electrically controlled. The gas carburetor mounted on the engine supplies gas to the engine through a needle valve. Adjustment to the gas flow rate can be made by turning the needle valve screw. Changes in the air fuel ratio can be made by attaching a stepper motor to the screw. The stepper motor used rotates with 7.5 degree steps and for each step, the equivalence ratio changed by about 0.006 for rich mixtures and by about 0.06 for lean mixtures, with a 0.012 change in equivalence ratio near stoichiometry.

ELECTRONIC CONTROLLER DESIGN

First, a check was made to see if the oxygen sensor does have a step response at about an equivalence ratio of 1.03. Figure 1 shows oxygen sensor voltage versus equivalence ratio for an ignition timing range of 10.8 to 32 BTDC. It can be seen that there is scatter and there are few data points on the actual step response indicating that small changes in air fuel ratio cause the voltage to step at the critical point. The scatter shows voltage step changes in the range of equivalence ratios from 1.02 to 1.06.

Since, in this system, the air fuel ratio is controlled by a stepper motor, it is of interest to know how the oxygen sensor responds to each step, especially at the point where the abrupt change of voltage output from the sensor is expected. It is also necessary to know the delay between stepper motor motion and the change in voltage at the sensor, so the speed of the controller can be designed.

Figure 2 shows the response of the oxygen sensor for changes in air fuel ratio from rich to lean. The figure shows three steps of the stepper motor. The fastest rate at which the instrumentation can sample the sensor voltage is 2.5 times each second and it can be seen that the sensor has, in most cases, almost reached its final value in less



2600 W LOAD

Figure 1. Oxygen sensor voltage vs. equivalence

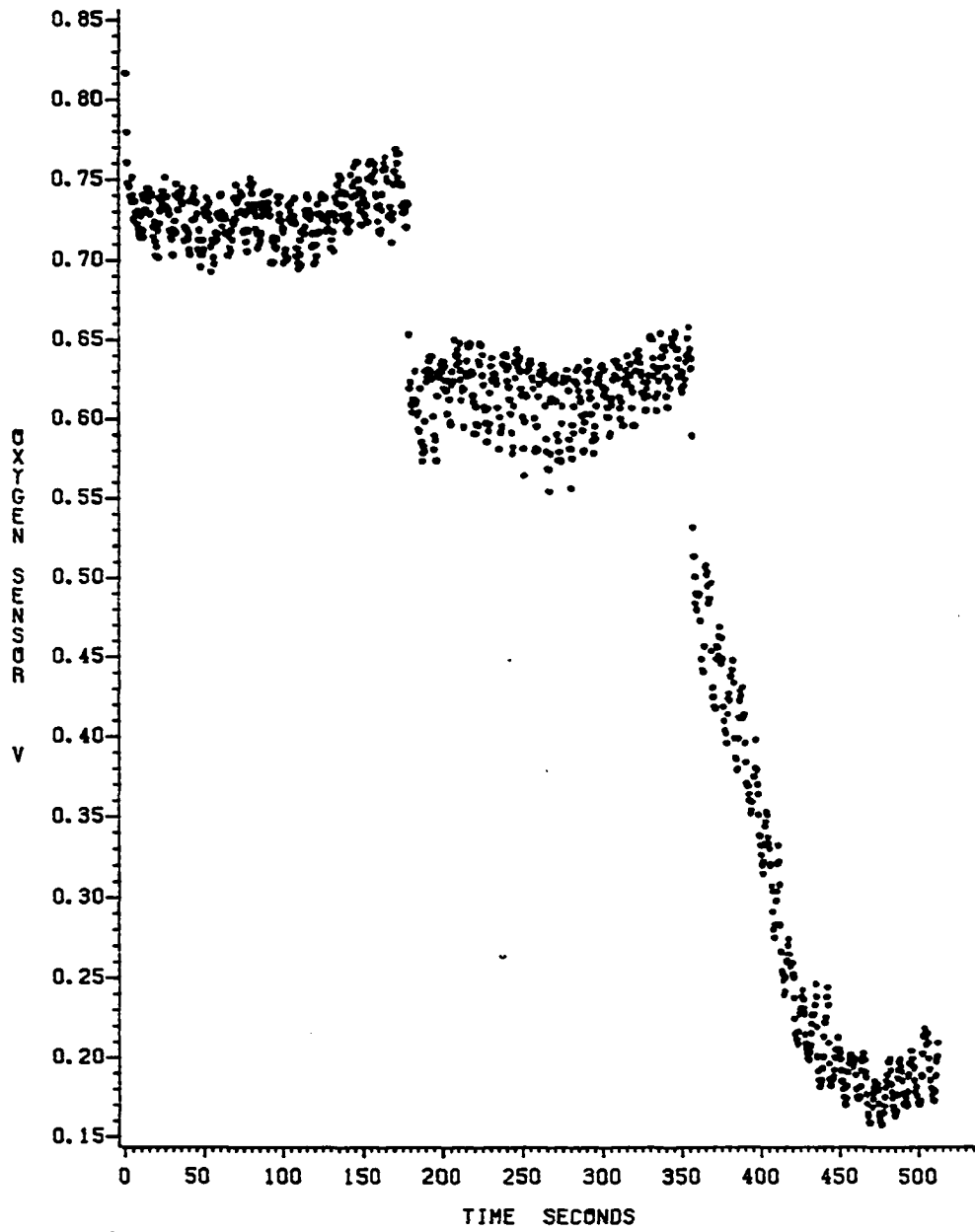


Figure 2. Response time of the oxygen sensor to step changes in air fuel ratio

than 0.8 s (1 to 2 samples of the data logger). The data logger samples the oxygen sensor for about 180 seconds after the motor step and it can be seen that in the third step the voltage continues to fall. This could be caused by a gradual change in the contents of the exhaust gas. The sensor is very sensitive at this critical point.

From Figure 1 it appears that by adjusting the stepper motor so that the oxygen sensor output voltage is somewhere between 100 and 500 mV, the equivalence ratio will be near 1.05. A circuit, therefore, has to be designed to start the stepper motor when the sensed voltage is out of the 100 to 500 mV range and step the motor in the right direction to make the correction.

Figure 3 shows the circuit used. It consists of a window comparator, pulse timer, and stepper motor driver. The components used in this circuit were chosen because they only need a single voltage supply and can be energized by a 12 V auto battery. The window comparator is made with two of the four operational amplifiers in a LM324 chip (National Semiconductor 1980). One amplifier monitors the upper limit voltage, and its output is saturated (high) when the oxygen sensor voltage exceeds 500 mV. The other amplifier output is saturated when the oxygen sensor voltage falls below 100 mV. These limits of 500mV and 100 mV are set by the

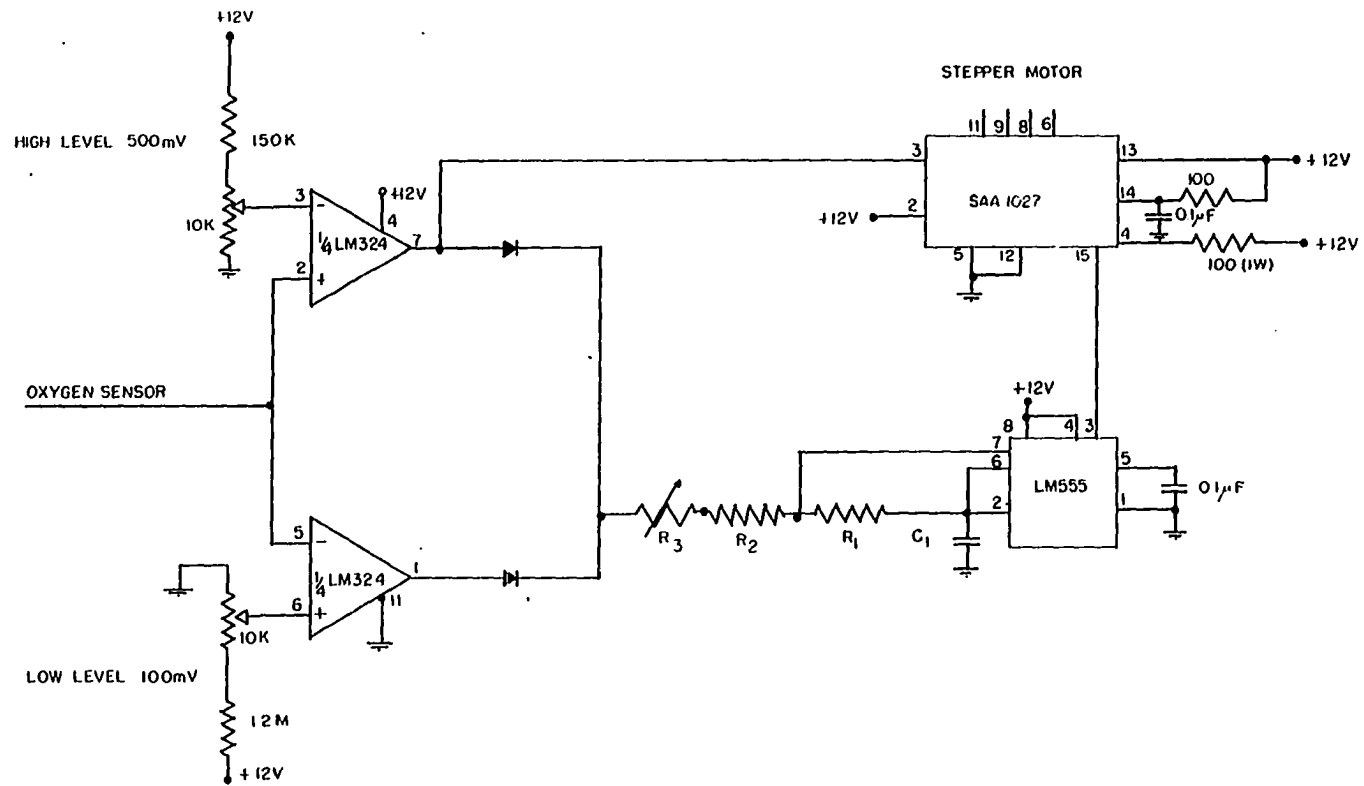


Figure 3. Controller circuit

potentiometers (Figure 3) and will vary slightly with fluctuations in the supply voltage. The operational amplifier outputs are combined by diodes and used to charge the timing capacitor of the LM555 timer (National Semiconductor 1980). The timer is wired as a frequency generator, and the output is connected directly to a SAA 1027 stepper motor driver (Airpax Corporation, Cheshire Division, Cheshire Ind. Park, Cheshire, CT 06410) which controls the stepper motor. When the oxygen sensor voltage is inside the comparator window, the operational amplifier outputs are low, the timing capacitor of the LM555 does not charge, and pulses are inhibited. This stops the stepper motor. The stepper motor direction is controlled by the rotation input pin (R) of the stepper motor driver. A high voltage to this pin causes the stepper motor to rotate counter clockwise. A low input will cause the opposite rotation. By connecting this pin to the correct operational amplifier output, the stepper motor will step in the direction required to make the right adjustment to the air fuel ratio.

The speed of the stepper motor rotation is dependent on the magnitude of the timing capacitor (C_1) and the resistors R_1 , R_2 and R_3 (see Figure 3). The period of pulse is determined by the number of steps the motor takes to have

the oxygen sensor output cross the voltage window, and the response time of the sensor. It is assumed that regardless of the size of step change in air fuel ratio it takes about 0.8 s for the sensor output to reach its final value. In this time the stepper motor is required to adjust the air fuel ratio so that the final value of the oxygen sensor voltage is in the center of the voltage window. If it takes X steps of the stepper motor for the voltage to span the window, then the pulse rate (T) in seconds, is given by:

$$T \times (X/2) = 0.8.$$

For this system the number of steps is two, so the pulse period should be about 0.8 s. By setting $C_1 = 22 \mu\text{F}$, $R_1 = 1 \text{ k}\Omega$, $R_2 = 39 \text{ k}\Omega$ and $R_3 = 25 \text{ k}\Omega$ the output period of the LM555 can be varied from 0.6 to 1.0 s. This allows for adjustments to be made when the circuit is installed. These time periods are likely to be longer because the saturation output voltage of the operational amplifiers is only 10.5 V, instead of 12 V, so the capacitor will charge more slowly.

Starting the engine from cold when the sensor is cold does not cause a problem because a cold oxygen sensor with a $2.2 \text{ M}\Omega$ resistor load has a stable output of 125 mV, which is in the comparator window. The sensor will change from there, depending on the fuel mixture. Stopping the engine when it is hot causes more of a problem. The hot sensor

will detect a lean mixture when the exhaust gas is not present and replaced with air. This opens the needle valve, leaving the engine set to a very rich fuel mixture. Because of the cold starting conditions explained above the engine starts with a rich fuel mixture or will not start at all. If the circuit is disconnected as soon as the engine is stopped, this problem does not arise. This can be accomplished by connecting the circuit to the ignition switch.

RESULTS AND DISCUSSION

The described air fuel ratio controller was built and found to work satisfactorily. Tables 1 and 2 show data obtained when the equivalence ratio was being controlled by the air fuel ratio controller. The engine parameters being varied are engine timing and engine temperature. The only problem found with the system is that a large step change in engine load from low power output to full power output will stall the engine. This is because the needle valve in the carburetor does not open up quickly enough and starves the engine of gas. Modifications to the carburetor will be needed to overcome this problem.

Table 1. Stability of air fuel controller while advancing engine ignition timing BTDC

| Timing degrees | Air fuel ratio | Equivalence ratio | Timing degrees | Air fuel ratio | Equivalence ratio |
|-------------------|-------------------|----------------------|-------------------|-------------------|----------------------|
| 18.0 | 17.54 | 1.02 | 32.4 | 17.87 | 1.04 |
| 19.8 | 17.54 | 1.02 | 34.2 | 17.98 | 1.04 |
| 21.6 | 17.50 | 1.01 | 36.0 | 18.06 | 1.05 |
| 23.4 | 17.43 | 1.01 | 37.8 | 18.06 | 1.05 |
| 25.2 | 17.44 | 1.01 | 39.6 | 18.17 | 1.05 |
| 27.0 | 17.84 | 1.03 | 41.4 | 18.21 | 1.06 |
| 28.8 | 17.73 | 1.03 | 43.2 | 18.14 | 1.05 |
| 30.6 | 17.76 | 1.03 | 45.0 | 18.19 | 1.05 |

Engine coolant temperature = 85 ± 1 C
 Electrical power = 3400 W (57% full load)

Table 2. Stability of air fuel ratio controller while changing engine coolant temperature

| Engine temp C | Air fuel ratio | Equivalence ratio | Engine temp C | Air fuel ratio | Equivalence ratio |
|------------------|-------------------|----------------------|------------------|-------------------|----------------------|
| 94.4 | 18.10 | 1.05 | 70.0 | 18.03 | 1.04 |
| 91.1 | 18.06 | 1.05 | 65.7 | 18.11 | 1.05 |
| 85.4 | 18.23 | 1.06 | 59.7 | 18.28 | 1.06 |
| 79.1 | 17.94 | 1.04 | 54.9 | 18.15 | 1.05 |
| 75.9 | 18.02 | 1.04 | 51.0 | 18.03 | 1.04 |

Ignition timing = 27 degrees BTDC
Electrical power = 3400 W (57% full load)

Better control of the equivalence ratio could be accomplished by increasing the number of steps the stepper motor takes to change the air fuel ratio and by narrowing the comparator window to voltages of 90 mV to 200 mV. The comparator should not be narrowed too much or lowered below 90 mV; thus variations in oxygen sensors do not affect the operation of the circuit.

The advantage of this type of system is that it will work for any type of spark ignition internal combustion engine fuel, provided the carburetor can be designed to operate with different fuels. This could be useful in a farm situation where the availability of biogas may not always be reliable. Adjustments to the ignition timing will be necessary for prolonged operation on different fuels.

CONCLUSIONS

1. A commercially produced ZrO_2 exhaust gas oxygen sensor was found have a voltage step change from approximately 850 to 70 mv when the equivalence ratio range was about 1.03 to 1.06.

2. By using a window comparator circuit the oxygen sensor can be used to successfully control the equivalence ratio at about 1.05 without a microprocessor. This is within the range of 1.03 to 1.15.

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SUMMARY AND DISCUSSION

The instrumentation system developed for this project performed well and gave consistent results. It would be beneficial to recalibrate the system to see how well it performs over time. Improvements to the coolant measurement system could be made by installing a flow meter more suited to the flow rates being measured. If both the power meter and the coolant meter were replaced with analog meters the system could update data faster than once a minute. In general, objective 1 is satisfied.

The second paper gives the details of controlling ignition timing, air fuel ratio, and coolant temperature. This has been accomplished and a relation between air fuel ratio and ignition timing was found. Further work needs to be conducted to find the optimum coolant temperature. The following optimum conditions were found for equivalence ratio and ignition timing for near full load:

| energy | equivalence range | ignition timing |
|------------|-------------------|-------------------------|
| electrical | 1.1 to 1.26 | 23 BTDC |
| thermal | 1.03 to 1.19 | not strongly dependent |
| total | 1.03 to 1.15 | not strongly dependent. |

The percentage of gas converted to electrical energy was

found to be greatest near full load. The thermal energy conversion declined as the load increased; but the total energy converted remained approximately unchanged.

The air fuel ratio controller worked satisfactorily keeping the equivalence ratio at about 1.05 for different operating conditions. Some improvements should be made to handle sudden changes in electrical load.

So far all the experimentation has been capturing electrical and thermal energy without making any alterations to the engine generator system. By this method, about 60% of the gas energy converted is captured, with the remainder being mostly lost as heat in the exhaust gas and by convection and radiation from the engine itself. With the data logger it is feasible to calculate the heat loss in the exhaust gas by calculating a molecular balance on the engine and by measuring the exhaust gas temperature. The latent heat of the water vapor in the exhaust should not be included in this calculation if the lower heating value of methane is used to calculate the percentage of gas energy converted. Currently, the exhaust gas temperature is being measured by a thermocouple attached to the surface of the exhaust pipe. A temperature probe placed in the exhaust gas should be used to check the thermocouple's measurement of actual exhaust gas temperature.

To reduce convection and radiation losses, it may be possible to insulate the engine. Provided the engine is supplied with sufficient coolant it should not overheat. Additional thermal energy will then be captured in the coolant.

An important item for further study is to add carbon dioxide to the natural gas so as to simulate biogas. The optimums should be checked to see if they are the same when operating on simulated biogas.

APPENDIX LISTING OF THE BASIC PROGRAM
USED BY THE DATA LOGGER


```

10 GOTO 1660
20 CALL 35328
30 FOR I = 0 TO CH
40 L = L2 + 5 * I
50 FOR I2 = 0 TO 4
60 R$ = R$ + CHR$ ( PEEK (L + I2))
70 NEXT
80 V = VAL (R$):R$ = ""
90 M(I) = M(I) + V
110 NEXT
120 M = PEEK (L + I2) + HB * PEEK (L + I2 + 1)
130 S(I) = S(I) + M * M:M(I) = M(I) + M
140 K = K + 1:I = I + 1:I2 = I2 + 2
150 IF PEEK (L3) = 1 THEN M = PEEK (L + I2) + HB * PEEK
(L + I2 + 1):I2 = I2 + 2:K1 = K1 + 1:S(I) = S(I) + M *
M:M(I) = M(I) + M
160 I = I + 1
170 IF PEEK (L4) = 1 THEN M = PEEK (L + I2) + HB * PEEK
(L + I2 + 1):I2 = I2 + 2:K2 = K2 + 1:S(I) = S(I) + M *
M:M(I) = M(I) + M
180 IF PEEK (L5) = 0 THEN GOTO 20
190 FOR I = 0 TO 4
200 R$ = R$ + CHR$ ( PEEK (L + I2 + I))
210 NEXT
220 FOR I = 0 TO CH + 1
230 DA(I) = M(I) + DA(I)
240 M(I) = M(I) / K
250 NEXT
260 DA(CH + 2) = DA(CH + 2) + M(CH + 2):DA(CH + 3) = DA(CH +
3) + M(CH + 3)
270 IF M(CH + 1) > 0 THEN M(CH + 1) = 60 * HZ / M(CH + 1) /
1E - 6
280 IF M(CH + 2) > 0 THEN M(CH + 2) = 54E6 * K1 * HZ / M(CH
+ 2)
290 IF K2 > 0 THEN QW = 7.918 * M(CH + 3) / K2 * (M(4) -
M(5)):MW = 0.11355 * M(CH + 3) / K2
300 MA = FN MA(M)
310 MG = FN MG(M)
312 MX = MG * 1000 / 16:MY = MA * 1000 / 28.964
320 O2 = M(0) * 1000
330 TR = M(8)
335 AF = MA / MG
340 IF AF > 17.26 THEN MX = MY / 9.524
345 EE = FN EE(TR)
350 EC = ET - M(4)
360 PRINT D$;"PR#1"

```

```

370 PRINT PR$;"80N";
380 & PRINT
USEA2$;R$,EE,M(10),QW,MW,M(4),M(6),MA,MG,AF,O2,TR
390 PRINT D$;"PR#0"
400 VTAB 20: PRINT : PRINT
410 PRINT D$;AP$;N$;" ,SO"
420 PRINT D$;W$;N$
430 & PRINT
USEA2$;R$,M(9),M(10),QW,MW,M(4),M(6),MA,MG,AF,O2,TR
440 PRINT D$;CL$;N$
450 PRINT D$;"PR#0"
460 FOR I = 0 TO CH + 3
470 M(I) = 0
480 NEXT
490 R$ = ""
500 VTAB 15
510 HTAB 4: PRINT "K = ";K
520 H = H + K:H1 = H1 + K1:H2 = H2 + K2
530 K = 0:K1 = 0:K2 = 0
540 J = J + 1
550 IF ABS (EC) > 1 THEN J5 = INT (J4 / 2): GOSUB 1270
560 IF J < J2 THEN 20
570 IF DA(CH + 2) > 0 THEN M(CH + 2) = 54E6 * H1 * HZ /
DA(CH + 2):S(CH + 2) = (S(CH + 2) - (DA(CH + 2) ^ 2) / H1) /
(H1 - 1)
580 FOR I = 0 TO CH + 1
590 M(I) = DA(I) / H
600 S(I) = (S(I) - H * M(I) * M(I)) / (H - 1)
610 NEXT
620 IF M(CH + 1) > 0 THEN M(CH + 1) = 60 * HZ / M(CH + 1) /
1E - 6
630 IF H2 > 0 THEN QW = 7.918 * DA(CH + 3) / H2 * (M(4) -
M(5))
640 IF H2 > 1 THEN MW = 0.11355 * DA(CH + 3) / H2:S(CH + 3)
= (S(CH + 3) - (DA(CH + 3) ^ 2) / H2) / (H2 - 1)
650 MA = FN MA(M)
660 MG = FN MG(M)
670 AF = MA / MG
680 O2 = M(0) * 1000
690 TR = M(8)
692 MX = MG * 1000 / 16:MY = MA * 1000 / 28.964
694 IF AF > 17.26 THEN MX = MY / 9.524
696 EE = FN EE(TR)
710 PRINT D$;"PR#1"
720 PRINT PR$;"80N";
730 PRINT
740 & PRINT USEA3$;EE,M(10),QW,MW,M(4),M(6),MA,MG,AF,O2,TR

```

```

760 & PRINT USEC1$;TM
770 PRINT D$;"PR#0"
780 VTAB 20: PRINT : PRINT
790 PRINT D$;AP$;N1$,"S6,D1"
800 PRINT D$;W$;N1$
810 & PRINT
USEB1$;M(9),M(10),QW,MW,M(4),M(6),MA,MG,AF,02,TR,TM
820 PRINT D$;CL$;N1$
830 PRINT D$;AP$;N2$,"S6,D1"
840 PRINT D$;W$;N2$
850 & PRINT USEB2$;SR,SP,SQ,SW,S(4),S(6),SA,SG,SA +
SG,S(0),S(8)
860 PRINT D$;CL$;N2$
870 PRINT D$;"PR#0"
880 FOR I = 0 TO CH + 3
890 M(I) = 0:S(I) = 0:DA(I) = 0
900 NEXT
910 PRINT D$;O$;N$;"S0"
920 PRINT D$;RE$;N$
930 FOR I = 1 TO J2
940 INPUT R$(I)
950 NEXT
960 PRINT D$;CL$;N$
970 PRINT D$;AP$;N$;"S6,D1"
980 PRINT D$;W$;N$
990 FOR I = 1 TO J2
1000 PRINT R$(I)
1010 NEXT
1020 PRINT D$;CL$;N$
1030 PRINT D$;"DELETE";N$;"S0"
1040 PRINT D$;O$;N$;"S0"
1050 PRINT D$;W$;N$
1060 PRINT D$;CL$;N$
1070 PRINT D$;"PR#1"
1080 PRINT PR$;"80N";
1090 PRINT : PRINT : PRINT A1$: PRINT A5$
1100 PRINT D$;"PR#0"
1110 VTAB 20: PRINT : PRINT
1120 J = 0:H = 0:H1 = 0:H2 = 0
1130 GOSUB 3130
1140 GOSUB 1160
1150 GOTO 20
1160 L = L2 + 20
1170 IF ABS (EC) > 1 THEN J5 = INT (J4 / 2)
1180 CALL 35328
1190 FOR I = 0 TO 4
1200 R$ = R$ + CHR$ ( PEEK (L + I))

```

```

1210 NEXT
1220 EA = EA + VAL (R$):R$ = ""
1230 I2 = I2 + 1
1231 L9 = 47
1232 IF PEEK (L3) = 1 THEN L9 = 49
1234 IF PEEK (L4) = 1 THEN WA = PEEK (L2 + L9) + HB *
PEEK (L2 + L9 + 1): VTAB 15: PRINT 0.11355 * WA
1240 IF PEEK (L5) = 0 THEN 1160
1250 EC = ET - EA / I2
1260 IF ABS (EC) < 1 THEN 1330
1270 E1 = 14 * ABS (3 * EC - 2 * EC2)
1280 IF E1 > 255 THEN E1 = 255
1290 IF EC * E2C < 0 AND EC > 0 THEN POKE - 29706,5: CALL
- 29766
1295 IF EC * E2C < 0 AND EC < 0 THEN POKE - 29706,4: CALL
- 29766
1300 E2C = EC
1310 IF EC > 0 THEN POKE - 29704,E1: CALL - 29795: GOTO
1330
1320 POKE - 29704,E1: CALL - 29824
1330 I2 = 0:EA = 0
1340 J5 = J5 + 1: IF J5 < J4 THEN 1160
1350 J5 = 0
1360 POKE 0,106: POKE 0,10
1370 RETURN
1380 REM COMMUNICATION ROUTINE
1390 FOR I = 1 TO LEN (TM$)
1400 POKE 36096 + I, ASC ( MID$ (TM$,I,1))
1410 NEXT I
1420 POKE 36097 + LEN (TM$),13
1430 POKE 36096, LEN (TM$) + 1
1440 RETURN
1450 POKE 0,4
1460 FOR I = 1 TO 4000: NEXT
1470 POKE 0,10
1480 CALL - 29795
1490 F8 = F8 + 1: FOR I = 1 TO 300: NEXT
1500 IF F8 < 45 THEN 1480
1510 POKE - 29703,30
1520 RETURN
1530 REM STANDARD ERRORS
1540 SQ = (7.918 ^ 2) * ((M(4) - M(5)) ^ 2 * S(11) + (DA(11)
/ H2) ^ 2 * (S(4) + S(5))): IF SQ > 0 THEN SQ = SQR (SQ)
1550 IF DA(9) > 0 THEN SR = (60E + 6 * HZ * H * H / DA(9) /
DA(9)) ^ 2 * S(9): IF SR > 0 THEN SR = SQR (SR)
1560 IF DA(10) > 0 THEN SP = (54E6 * H1 * H1 * HZ / DA(10)
/ DA(10)) ^ 2 * S(10): IF SP > 0 THEN SP = SQR (SP)

```

```

1570 SG = ( FN D1(M(1))) ^ 2 * S(1) + ( FN D2(M(7))) ^ 2 *
S(7) + ( FN D3(M(2))) ^ 2 * S(2): IF SG > 0 THEN SG = SQR
(SG)
1580 SA = ( FN B1(M(3))) ^ 2 * S(3) + ( FN B2(M(6))) ^ 2 *
S(6): IF SA > 0 THEN SA = SQR (SA)
1590 FOR I = 0 TO CH + 3
1600 IF S(I) > 0 THEN S(I) = SQR (S(I))
1610 NEXT
1620 S(0) = S(0) * 1000
1630 SW = 0.11355 * S(11)
1640 S(8) = S(8)
1650 RETURN
1660 D$ = CHR$ (4):PR$ = CHR$ (9)
1670 ST = 3
1680 PRINT D$;"BLOAD DATA1.1,S0"
1685 PRINT D$;"BLOAD O2"
1690 PRINT D$;"BRUN PRINT USE"
1695 HIMEM: 14000
1697 D$ = CHR$ (4):PR$ = CHR$ (9)
1698 ST = 3
1700 O$ = "OPEN":R$ = "READ":W$ = "WRITE":AP$ =
"APPEND":CL$ = "CLOSE":DE$ = "DELETE"
1710 HOME
1720 PRINT "SET PRINTER"
1730 PRINT "PUT IN DATA DISC"
1740 INPUT "DATA FILE NAME ";N$
1750 N1$ = N$ + "M"
1760 N2$ = N$ + "S"
1770 INPUT "NUMBER OF MINUTES TO RUN PER DATA SET";J2
1780 INPUT "NUMBER OF MINUTES BETWEEN RUNS ";J4
1790 INPUT "PRESSURE IN INS.HG ";PR
1800 INPUT "HUMIDITY ";HU
1810 PR = PR * 3.37685E + 3
1820 INPUT "TIMING(%) XX.X ";R$
1830 X1 = VAL ( LEFT$ (R$,1))
1840 X2 = VAL ( MID$ (R$,2,1))
1850 X3 = VAL ( RIGHT$ (R$,1))
1860 X1 = X1 + X2 * 16
1870 X4 = VAL (R$)
1880 R$ = ""
1890 TM = (100 - X4) * 1.8
1900 INPUT "ENGINE TEMP ";ET
1910 REM FUNCTIONS
1920 DEF FN G1(M1) = 21.2134 * (M1 - 0.096)
1930 DEF FN G2(M7) = (( FN G1(M(1))) / (1028.72 + 3.1379 *
M7) + 7.102E - 3) * 0.11547 / (M7 + 273.2)
1940 DEF FN G3(M2) = (PR + (0.7751 + 1.706 * M2) * 249)

```

```

1950 DEF FN MG(M) = ( FN G2(M(7))) * ( FN G3(M(2))): REM
GAS FLOW
1960 REM GAS DIF.
1970 DEF FN D1(M1) = 2.4496 / (1028.72 + 3.1379 * M(7)) /
(M(7) + 273.2) * ( FN G3(M(2)))
1980 DEF FN D2(M7) = - ((( FN G1(M(1))) * 0.36233) /
((1028.72 + 3.1379 * M7) ^ 2) / (M7 + 273.2) + (( FN
G1(M(1))) / (1028.72 + 3.1379 * M7) + 7.102E - 3) * .11547 /
((M7 + 273.2) ^ 2)) * ( FN G3(M(2)))
1990 DEF FN D3(M2) = 424.79 * ( FN G2(M(7)))
2000 REM AIR FLOW
2010 DEF FN PR(M6) = PR - HU * (167.928 - 7.5219 * M6 +
0.5472 * M6 * M6)
2020 DEF FN A1(M3) = 0.0162748 * (1.8266 * M3 - 0.01562) *
( FN PR(M(6)) - (0.0296 + 0.2938 * M3 + 0.05474 * M3 * M3) *
249)
2030 DEF FN A2(M6) = (1.053 - 2.508E - 3 * M6) / (M6 +
273.2)
2040 DEF FN MA(M) = ( FN A1(M(3))) * ( FN A2(M(6)))
2050 DEF FN B1(M3) = (0.029728 * ( FN PR(M(6)) - (0.0296 +
0.2938 * M3 + 0.05474 * M3 * M3) * 249) - 0.0162748 *
(1.8266 * M3 - 0.01562) * (0.2938 + 0.10948 * M3) * 249) * (
FN A2(M(6)))
2060 DEF FN B2(M6) = ( - 2.508E - 3 / (M6 + 273.2) -
(1.053 - 2.508E - 3 * M6) / ((M6 + 273.2) ^ 2)) * ( FN
A1(M(3))) - HU * ( - 7.5219 + 1.0944 * M6) * 0.0162748 *
(1.8266 * M(3) - 0.01562) * ( FN A2(M(6)))
2065 DEF FN EE(TR) = ((MX * 27.076 + MY * 5.5971 + (MY -
9.524 * MX) * 1.5493) * ((TR - 57) * 4.192 / 3600 + 2367 *
18 * 2 * MX / 3600
2070 A1$ = "TIME QEXH POWR QWATR MWATR TWATR TAIR
MAIR MGAS A/F O2 EX T"
2080 A2$ = "##### ##### ##### ##### #.### #.### #.###
#.### #.### #.### #.### #.###"
2090 A3$ = "MEAN ##### ##### ##### #.### #.### #.###
#.### #.### #.### #.### #.###"
2100 A4$ = "S.ER. #.### #.### ##### .### #.### #.###
#.### .### #.### #.### #.###"
2110 A5$ = " (W) (W) KG/M (C) (C)
KG/H KG/H (C)"
2120 B1$ = "#### #.###^#### #.###^#### #.### #.### #.###
#.### #.### #.### #.###^#### #.###^#### #.###^####"
2130 B2$ = "#.###^#### #.###^#### #.###^#### #.###^####
#.###^#### #.###^#### #.###^#### #.###^#### #.###^####
#.###^####"
2140 C1$ = "TIMING= #.### DEGREES ADVANCE"
2150 C2$ = "DATA FILE ##### ATMOS P. #####(PA)

```

```

HUMIDITY ##(%)  ENG TEMP ##.##(C)"
2160 PRINT D$;"PR#1"
2170 PRINT PR$;"80N"
2180 & PRINT USEC2$;N$,PR,HU,ET
2190 HU = HU / 100
2200 PRINT
2210 PRINT A1$
2220 PRINT A5$
2230 PRINT D$;"PR#0"
2240 VTAB 20: PRINT : PRINT
2250 PRINT D$;O$;N$
2260 PRINT D$;"DELETE";N$
2270 PRINT D$;O$;N$
2280 PRINT D$;W$;N$
2290 PRINT D$;CL$;N$
2300 PRINT D$;O$;N$;"",S6,D1"
2310 PRINT D$;"DELETE";N$
2320 PRINT D$;O$;N$
2330 PRINT D$;W$;N$
2340 PRINT D$;CL$;N$
2350 PRINT D$;O$;N1$
2360 PRINT D$;"DELETE";N1$
2370 PRINT D$;O$;N1$
2380 PRINT D$;W$;N1$
2390 PRINT D$;CL$;N1$
2400 PRINT D$;O$;N2$
2410 PRINT D$;"DELETE";N2$
2420 PRINT D$;O$;N2$
2430 PRINT D$;W$;N2$
2440 PRINT D$;CL$;N2$
2450 L2 = 35857:HB = 256:HZ = 1.023:L3 = 35824
2460 L4 = 35825:L5 = 35826
2470 HOME
2480 P = - 15104
2490 O = - 14976
2500 POKE P + 2,255
2510 POKE O + 2,127
2520 POKE P + 3,255
2530 POKE O + 3,0
2540 POKE O + 11,192
2550 POKE O + 4,75
2560 POKE O + 5,76
2570 POKE P + 1,X1
2580 POKE P,X3
2590 POKE O,4
2600 DIM DA(12),R$(100)
2610 DIM M(15),S(15)

```

```

2620 POKE - 16140,3
2630 POKE - 16140,1
2640 POKE - 29706,4
2650 POKE - 29704,30
2660 POKE - 29703,100
2670 POKE - 29705,200
2680 TN$ = "0"
2690 TR$ = "8"
2700 I3 = VAL (TN$):I4 = VAL (TR$)
2710 CN$ = "*0:"
2720 TM$ = "ACT/" + TN$ + "/" + TR$
2730 TM$ = CN$ + TM$ + ":"
2740 GOSUB 1380
2750 POKE 35856,1
2760 CALL 35328
2770 TM$ = "FSC:"
2780 TM$ = CN$ + TM$
2790 GOSUB 1380
2800 CH = I4 - I3
2810 X = (CH + 1) * 5 + 1
2820 POKE 35856,X
2830 VTAB 1
2840 FOR I = 0 TO CH
2850 HTAB 6: PRINT "CHANNEL";I3;" = "
2860 I3 = I3 + 1
2870 NEXT
2880 GOSUB 1450
2890 FOR I = 0 TO 1
2900 ST = ST - 1
2910 POKE 0,ST
2920 FOR I2 = 1 TO 200: NEXT
2930 S2 = 2
2940 GOTO 1140
2950 IF AF > 17 AND AF < 18.5 THEN 3370
2955 IF AF > 21 THEN GOTO 3070
2960 IF AF > 16 THEN S2 = 1
2970 IF AF > 17.5 THEN S2 = 0
2980 FOR I2 = 0 TO S2
2990 ST = ST + 1:S1 = S1 + 1
3000 IF ST = 4 THEN ST = 0
3010 POKE 0,ST
3020 FOR I = 1 TO 200: NEXT
3030 NEXT
3040 POKE 0,11
3050 I = 0:I2 = 0
3060 RETURN
3070 FOR I = 1 TO S1

```



```

3080 ST = ST + 1: IF ST = 4 THEN ST = 0
3090 POKE 0,ST
3100 FOR I2 = 1 TO 200: NEXT
3110 NEXT
3120 S1 = 0:S2 = 2: POKE 0,11
3130 X4 = X4 - 1.0
3140 IF X4 < 75 THEN STOP
3150 R$ = STR$ (X4)
3160 X1 = VAL ( LEFT$ (R$,1))
3170 X2 = VAL ( MID$ (R$,2,1))
3180 X3 = VAL ( RIGHT$ (R$,1))
3190 X1 = X1 + X2 * 16
3200 POKE P + 1,X1
3210 POKE P,X3
3220 TM = (100 - X4) * 1.8:R$ = ""
3230 I = 0:I2 = 0
3240 RETURN
3370 REM OXYGEN SENSOR RESPONSE
3380 TM$ = "*0:ACT/0/0"
3382 GOSUB 1390
3383 POKE 35856,1
3384 CALL 35328
3386 TM$ = "*0:CHA/0:"
3390 GOSUB 1390
3402 N3$ = N$ + "02" + STR$ (G2)
3404 G2 = G2 + 1
3406 PRINT D$;O$;N3$;" ,S6,D1"
3408 PRINT D$;DE$;N3$
3410 PRINT D$;O$;N3$
3415 PRINT D$;W$;N3$
3417 PRINT "818"
3420 POKE - 28928,ST
3430 CALL - 28672
3440 LO = 29952
3450 R$ = STR$ ( PEEK (LO))
3460 FOR I = 1 TO 4
3470 R$ = R$ + CHR$ ( PEEK (LO + I))
3480 NEXT
3485 PRINT R$
3490 LO = LO + I
3492 FOR I = 0 TO 4
3495 R2$ = R2$ + CHR$ ( PEEK (LO + I))
3498 NEXT
3500 LO = LO + I
3530 PRINT R2$
3560 R$ = "" : R2$ = ""
3570 G = G + 2

```

```
3580 IF LO < 34036 THEN 3450
3630 PRINT D$;CL$;N3$
3635 VTAB 20: PRINT : PRINT
3640 G = 0
3650 ST = PEEK ( - 28928)
3652 TM$ = "*0:ACT/0/8:"
3654 GOSUB 1390
3655 S1 = S1 + 1
3656 CALL 35328
3660 TM$ = "*0:FSC:"
3665 POKE 35856,X
3670 GOSUB 1390
3680 RETURN
3690 REM WATER TEMP CHANGE
3700 ET = ET - 5
3710 RETURN
```